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Three-Stage Combustion (Reburning) on a Full Scale Operating Boiler in the USSR

Combustion Engineering Co., Windsor, CT

Prepared for:

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THREE-STAGE COMBUSTION (REBURNING) ON A FULL SCALE OPERATING BOILER IN THE U.S.S.R.

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16. ABSTRACT The report gives results of a program to complete the preliminary design of a three-stage combustion (reburn) system for nitrogen oxide (NOx) emissions control on an operating boiler in the U.S.S.R. The program to design the reburn system consisted of five tasks: visiting the Ladyzhinskaya host site to exchange design and operating information; translating Soviet documents into English; performing process calculations; conducting physical flow modeling; and developing a preliminary system design which included general arrangement drawings and furnace performance analyses. The overall preliminary reburn system design was presented to and accepted by Soviet representatives during a June 1989 meeting at the EPA's Air and Energy Engineering Research Laboratory (AEERL) in Research Triangle Park, NC. It appears that reburning would be a viable NOx reduction technology for the type of boiler represented by the host Ladyzhinskaya steam generating unit.

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a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Combustion	Stationary Sources	21B
Boilers	Reburning	13A
Design	Staged Combustion	14G
Nitrogen Oxides		07B
Emission		

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ABSTRACT

This report presents the results of a program to complete the preliminary design of a three-stage combustion (reburn) system for NO_x emissions control on an operating boiler in the U.S.S.R. This project was sponsored by the U.S. Environmental Protection Agency (EPA) in support of the protocol of the Eleventh Meeting of the Stationary Source Air Pollution Control Technology Working Group, Moscow, U.S.S.R., November, 1988.

The program to design the reburn system was comprised of the following five tasks: visiting the Ladyzhinskaya host site to exchange design and operating information; translating the Soviet documents into English; performing process calculations; conducting physical flow modeling; and developing a preliminary system design which included general arrangement drawings and furnace performance analyses.

The overall preliminary reburn system design was completed and was presented to and accepted by Soviet representatives during a June, 1989 meeting at the EPA's Air and Energy Engineering Research Laboratory (AEERL) in Research Triangle Park, N.C. It appears that reburning would be a viable NO_x reduction technology for the type of boiler that the host Ladyzhinskaya steam generating unit represents.

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The success of this program was due in large part to an open exchange of technical information between the U.S. and Soviet sides. We thank the staff of the Ladyzhinskaya Power Station, the Ukrainian Power Board, and VTI (All Union Heat Engineering Institute) for their support.

EXECUTIVE SUMMARY

The objective of this program was to systematically develop a preliminary design for a three-stage combustion (reburn) system for the 300 MWe type Tππ-312 Ladyzhinskaya steam generating unit located in Vinnitsa, U.S.S.R. This objective has been met and the preliminary design was accepted by the Soviet representatives monitoring this program during a meeting at EPA/AEERL in June, 1989.

The acceptance was qualified, however, in that the Soviets requested that a supplemental thermal performance sensitivity analysis be conducted on the key reburn process parameters in order to even further quantify any impacts that the reburn system would have on normal boiler operation. In addition, during the June, 1989 meeting the Soviet representatives presented additional information and clarification on the design and operational assumptions that were used in developing the preliminary reburn system design.

Future workscope in the three stage combustion (reburning) demonstration will include the Soviet side completing the detailed design of the system, then fabricating, retrofitting, and finally testing the system in the Ladyzhinskaya power station. Currently, the U.S. side would be involved in these phases in a review and consultative role.

The statements below summarize major elements of the preliminary design. Key findings related to the supplemental recommendations for the jointly accepted US/USSR preliminary reburn system design have also been included.

- The design is based on information transmitted from the Soviet side to the U.S. side during the Ladyzhinskaya plant tour hosted by the Soviet side in November, 1988; public domain reburning technology technical literature; and Combustion Engineering boiler design methodologies.

- The preliminary design employs natural gas as the reburn fuel and coal as the main burner fuel. The report highlights potential advantages and disadvantages of using fuel oil and coal as reburn fuels.

- The preliminary design meets design criteria for maximizing NO_x reductions for the process.

- To the extent possible, the preliminary design was developed consistent with the Soviet side directive that reburn system operation cannot affect slag tapping (wet slag removal from the furnace bottom), that temperature growth (with the reburn system in operation) must be within tube design limits, and that furnace slagging/fouling characteristics should not change. As designers of the Ladyzhinskaya unit, the Soviet side must corroborate the above through application of the their own design methodologies prior to establishing the final reburn system design.

- The preliminary design identifies major process flows for the main burners, reburn fuel injectors, and burnout air injectors. The total number of injectors as well as their elevational and planar locations, and their approximate free areas (cross sectional exit areas) have been established based on stoichiometric/residence time calculations, physical flow modeling, and boiler performance calculations. Detailed mechanical design of the system shall be the responsibility of the Soviet side.

- The preliminary design was generally comprised of twelve (12) reburn fuel injector windboxes located at elevation 20.3 meters, and twelve (12) burnout air injectors windboxes located at elevation 29.2 meters (Figure S-1). The reburn fuel (natural gas) represented 20% of the total heat input into the boiler. Recirculated flue gas (FGR) has been employed as a reburn fuel propelling medium; the quantity of FGR required was defined to be 10% by weight of the total boiler flue gas.

- The reburn fuel and burnout air injectors identified in the preliminary design are capable of vertically tilting and horizontally yawing. This design feature will enhance system performance optimization in the host boiler. Down tilt of the nozzles significantly enhanced mixing as was demonstrated by physical flow modeling.

- The reburn fuel nozzle configuration should be designed to achieve a jet velocity at the nozzle exit of 146-183 ft/sec (45-56 m/sec).

- The burnout air nozzle configuration should be designed to achieve a jet velocity at the nozzle exit of 183-229 ft/sec (56-70 m/sec).

- When reburning is employed, gas temperature in the furnace hopper should decrease by 50°F to 100°F (28°C to 56°C) and the furnace exit gas temperature should increase by 60°F to 70°F (35°C to 40°C).

  The cumulative waterwall steam heat absorption was predicted to decrease by about four (4) percent with natural gas reburning. The fly ash carbon content was anticipated to decrease slightly with natural gas reburning. And finally, no significant changes were predicted for the furnace waterwall metal temperatures.

- A supplemental thermal performance analysis and sensitivity study, which was based on information exchanged by the U.S./Soviet sides in June, 1989, resulted in several key design recommendations. These recommendations, if implemented in the Soviet final system design, will potentially improve NO_x reduction performance and further minimize the operational impacts of reburning on the Ladyzhinskaya boiler.

  In particular, it was determined that it would be desirable to: minimize the main burner excess air level; minimize the reburn fuel flow while maintaining the desired reburn zone stoichiometry; minimize the reburn injector flue gas recirculation (FGR) flow while maintaining effective mixing; and finally maintaining or increasing the upper furnace FGR flow and approximate location.

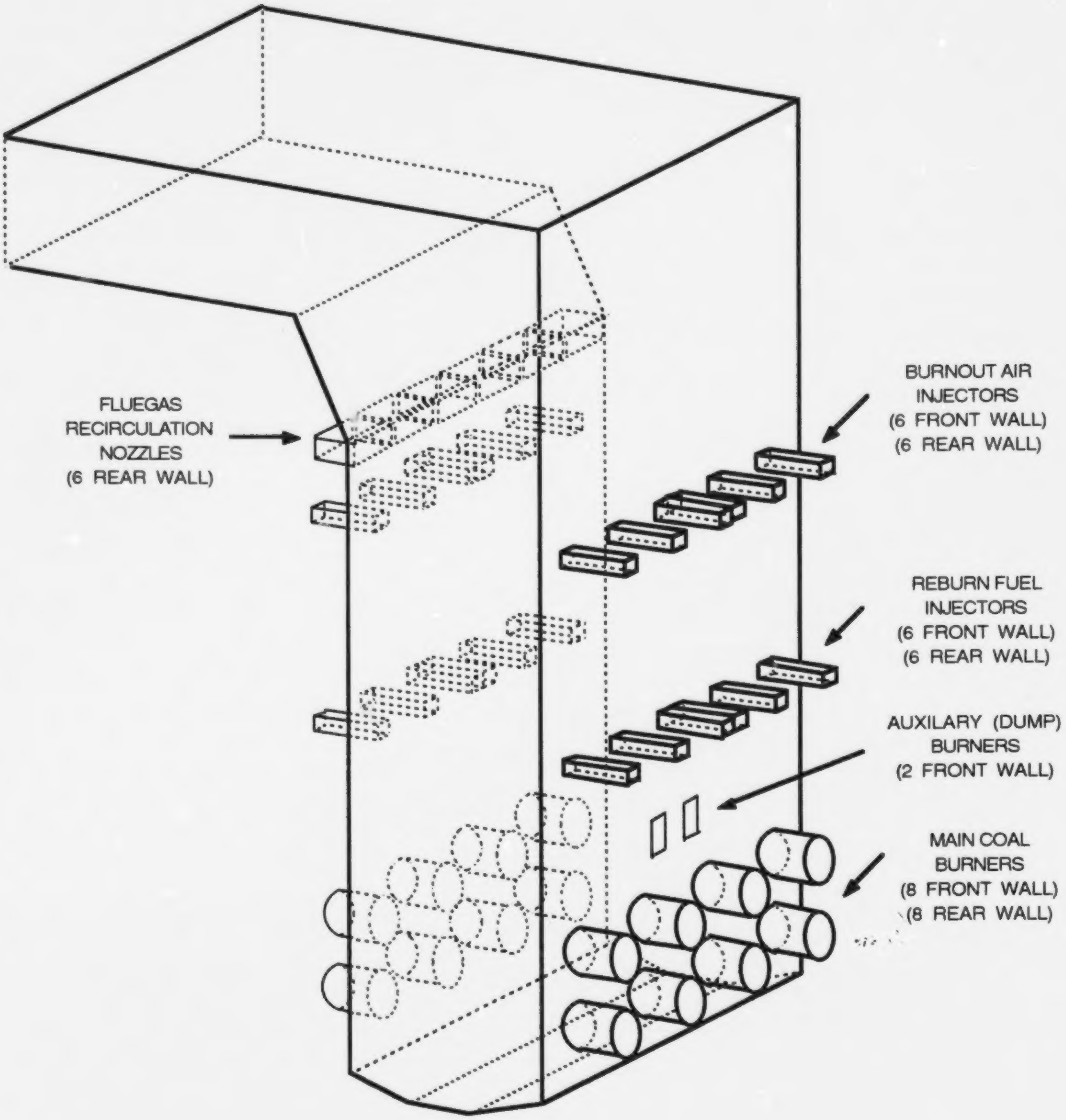
BURNOUT AIR
INJECTORS
(6 FRONT WALL)
(6 REAR WALL)
FLUEGAS
RECIRCULATION
NOZZLES
(6 REAR WALL)
REBURN FUEL
INJECTORS
(6 FRONT WALL)
(6 REAR WALL)
AUXILARY (DUMP)
BURNERS
(2 FRONT WALL)
MAIN COAL
BURNERS
(8 FRONT WALL)
(8 REAR WALL)

Figure S-1. Preliminary Reburn System Design Ladyzhinskaya Power Station, Vinnitsa, U.S.S.R.

SECTION 1

INTRODUCTION

It has been reported that NO_x plays an important role in the formation of acid rain (1,2,3). One important source of NO_x is utility boilers, particularly those which burn coal and to a lesser extent those which fire oil or natural gas. Three-stage combustion (reburning) represents a particular in-furnace NO_x reduction technique for which the Soviet wet bottom (slagging) boilers are well suited.

Under U.S. Environmental Protection Agency sponsorship, Combustion Engineering, Inc. has developed a preliminary design for a reburning system for a Soviet coal-fired boiler. The boiler chosen to represent the design case is located at the Ladyzhinskaya Power Station in Vinnitsa, U.S.S.R. (Figure 1-1). The power station is comprised of six (6) 300MWe coal fired boilers of the Soviet type Tππ -312 (Figure 1-2). These super critical (255 Kg/cm^2) steam pressure units employ swirl-stabilized opposed fired coal burners (sixteen per boiler) which burn locally available high volatile bituminous coals of relatively high (35%) ash content. The boilers operate under slagging conditions, that is, a portion (~30% by weight) of the ash is retrieved as wet slag at the furnace bottom, the remaining 70% by weight of ash input into the boiler is collected at the furnace outlet via electrostatic precipitators.

According to Soviet data, baseline NO_x emissions from these units typically range between 650-1300 $milligrams/NM^3$ @ 6% O_2 (0.5-1.0 $lb/10^6$ Btu). The

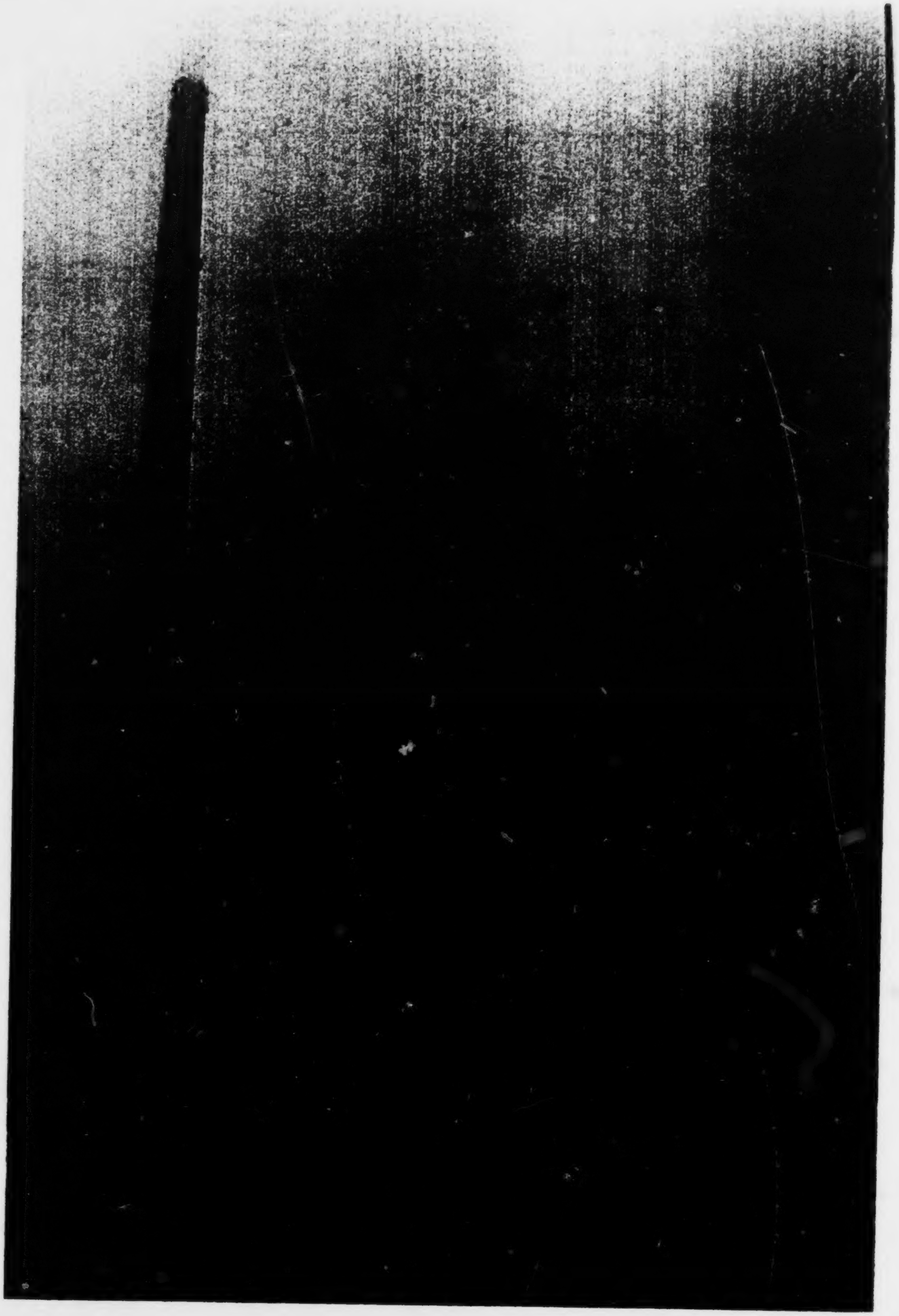

Figure 1-1. Ladyzhinskaya Steam Generator

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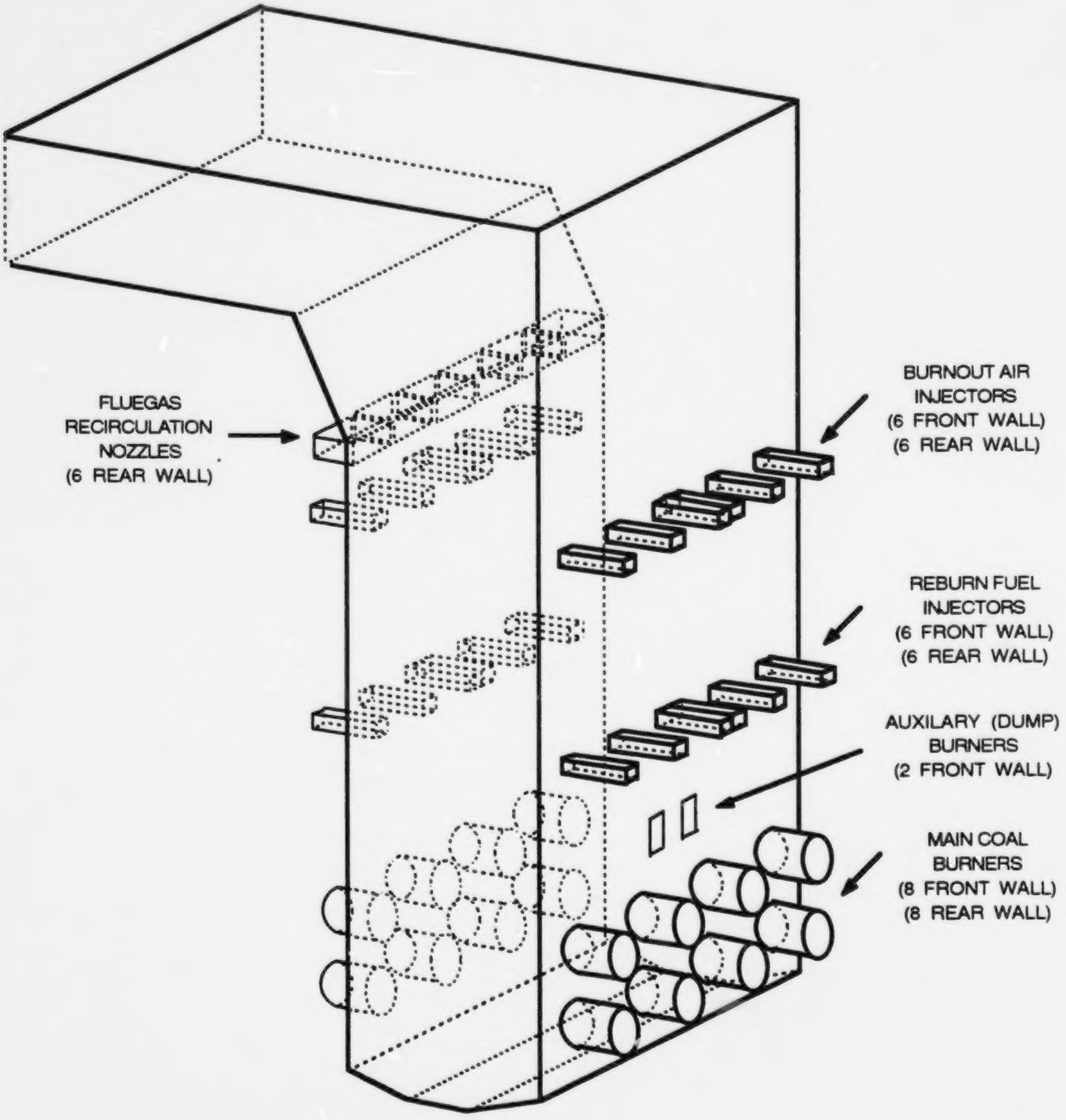

FLUEGAS
RECIRCULATION
NOZZLES
(6 REAR WALL)
BURNOUT AIR
INJECTORS
(6 FRONT WALL)
(6 REAR WALL)
REBURN FUEL
INJECTORS
(6 FRONT WALL)
(6 REAR WALL)
AUXILARY (DUMP)
BURNERS
(2 FRONT WALL)
MAIN COAL
BURNERS
(8 FRONT WALL)
(8 REAR WALL)

Figure 1-2. Preliminary Reburn System Design

emission levels are similar to those observed in coal fired units built in the United States, utilizing wall and cyclone type firing systems, prior to the implementation of federal New Source Performance Standards (NSPS) in 1971.

The Soviets have recognized that three-stage (reburn) combustion technology offers an opportunity to substantially reduce NO_x emissions on these units. The Soviets are currently planning to implement reburn technology at one of the six (6) Ladyzhinskaya units in order to demonstrate the commercial viability of reburn technology on this class of Soviet coal-fired boilers. If the demonstration is successful, the Soviets may extend use of the technology to other units at the Ladyzhinskaya station and elsewhere in the Soviet Union. The Soviets have stated that there are approximately 300 units of this class in the U.S.S.R..

PROJECT OBJECTIVE

The overall goal of this project was to develop a preliminary design for a three-stage combustion (reburn) system for application to an existing Soviet coal-fired boiler. The project focused on the use of natural gas as the reburn fuel, with coal as the main burner fuel. The preliminary design which has evolved can form the basis for the Soviet side to complete a final system design for implementation at the Ladyzhinskaya Power Station.

REBURN PROCESS OVERVIEW

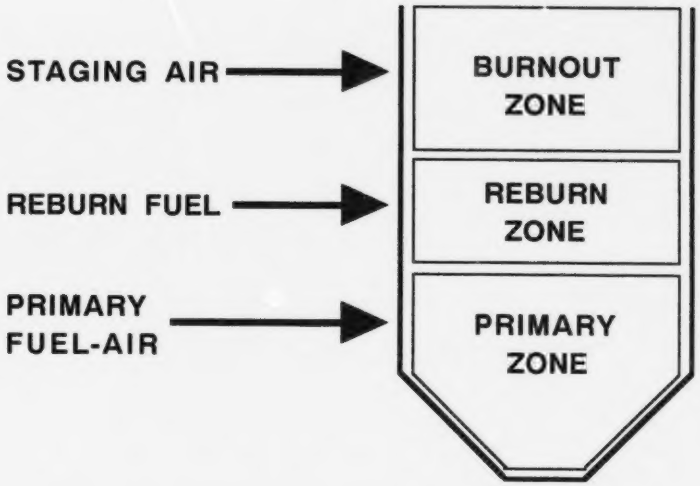
The concept of reburning or three stage combustion and the postulated chemical reactions which account for the reduction of NO_x in the reburn zone have been addressed elsewhere in the literature and will not be reiterated in detail here (4,5,6,7). Briefly, reburning is an in-furnace technique for reducing NO_x by creating a slightly reducing (sub-stoichiometric) zone downstream of the primary combustor as shown schematically in Figure 1-3. The reducing zone is created by introducing fuel into a zone with insufficient oxygen available to fully combust the fuel. The presence of a reducing zone creates intermediate nitrogen-containing species which subsequently react with previously formed NO_x to form the desired product, molecular nitrogen. Any unburned fuel leaving the reburn zone is subsequently burned to completion in the burnout zone.

Reburning can be used on all types of fossil fuel fired boilers (i.e., wall, tangential, and cyclone firing systems using coal, oil or natural gas fuel) and, in fact, has been successfully employed on a number of large utility oil fired boilers in Japan where oil has been used as the reburn fuel (8). The technology is particularly adaptable to slagging furnaces employing cyclone combustors or swirl stabilized burners similar to those used in the Ladyzhinskaya units. Since these combustors may not be able to tolerate significant changes to its operation, such as lower excess air or staged air injection, without the possibility for creating other problems (such as slag tapping: the removal of coal-ash slag through the furnace bottom while still in its molten state) they are limited to an in-furnace NO_x reduction technology that does not depend on significant changes to its present mode of operation. Reburning does not require that any significant operational changes be made to the primary combustor (or burners). The key requirement is that the fuel feed rate be reduced in the primary combustor with an equivalent amount (on a Btu basis) of fuel being injected into the reburn

DIVERTING PORTIONS OF THE FUEL AND COMBUSTION AIR STREAMS FROM THE MAIN BURNER(S) FOR INJECTION INTO THE POST FLAME GASES

MECHANISTIC MODEL FOR NOx DESTRUCTION

NOx FORMATION INHIBITED DUE TO FUEL RICH CONDITIONS IN REBURN ZONE; NOx DESTRUCTION IS PROMOTED DUE TO SECONDARY FLAME RADICAL ATTACK ON NO PRODUCED IN PRIMARY ZONE TO FORM MOLECULAR NITROGEN


STAGING AIR
BURNOUT ZONE
REBURN FUEL
REBURN ZONE
PRIMARY FUEL-AIR
PRIMARY ZONE

HYPOTHESIZED NOx DESTRUCTION MECHANISM:

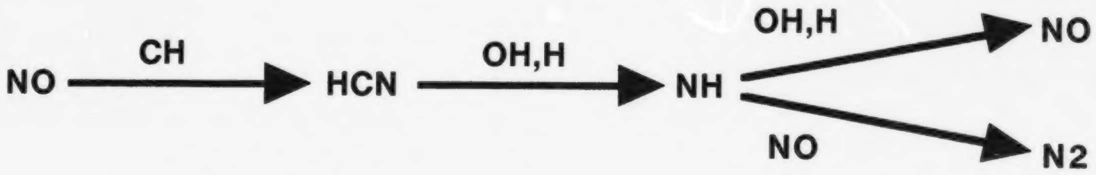

NO
CH
HCN
OH,H
NH
OH,H
NO
NO
N2

Figure 1-3. Basic Reburn Process Description

BASIC REBURN PROCESS

zone, usually not more than 20% of the total fuel input. The excess air, and hence the air/fuel stoichiometry within the main burner zone can be held constant thereby avoiding the potential for operational problems.

SECTION 2

INFORMATION FROM THE SOVIET SIDE

Boiler design information exchange between the U.S. and Soviet sides was vital to successfully developing a preliminary reburn system design for the Ladyzhinskaya Power Station. Information was exchanged during a tour by U.S. EPA and Combustion Engineering, Inc. representatives of the Ladyzhinskaya plant hosted by the Soviets in November, 1988. An information exchange meeting was organized, as part of the tour, at the plant, key management and operating personnel at the plant were available to review boiler design characteristics and answer questions about plant operation. This "one-on-one" meeting with the plant staff proved invaluable to the U.S. side, all questions raised by the U.S. side were answered. Information was transmitted to the U.S. side related to boiler steam side characteristics, typical fuel analysis, boiler thermal efficiency, furnace characteristics, the combustion air and flue gas recirculation systems, pulverized coal fineness, and burner characteristics. This information has been summarized in Table 2-1.

Additional information related to boiler design and operation was reviewed during the meeting at the Ladyzhinskaya plant. Typical unit turndown ratio, boiler ash management, and baseline NO_x levels were defined. Typical operating excess oxygen (O_2) levels, flue gas and natural gas constituent

Table 2-1. Design Characteristics of the Ladyzhinskaya Steam Generator

Boiler type - ТПП ("P" shaped")
- 312 (super critical once-thru with reheat)

Manufacture - Taganrog Boiler Works
Unit Rating - 300 MWe (6 unit's total @ Power Station

1.	Superheater outlet	1000T/Hr.
	Superheater outlet temperature	545°C
	Superheater outlet pressure	255 kg/cm^2
	Feedwater temperature	265°C
	RH outlet	780 T/hr.
	RH outlet temp	545°C
	RH outlet pressure	39 kg/cm^2
	RH inlet temperature	297°C
2.	Type of Fuel	
	Volatile content	42%
	Low coal heating value	3810 kcal/kg (15.95 MJ/kg)

Fuel Ultimate Analysis

Moisture W^P = 12%
Ash A^P = 35.2%
Sulfur = 0.9 - 2.0%

carbon C^P = 40.1%
hydrogen H^P = 3.0%
nitrogen N^P = 0.8%
oxygen O^P = 6.0%

(Continued)

Table 2-1. Continued

ASH ANALYSIS

SiO_2 = 52.3%
Al_2O_3 = 25.5%
TiO_2 = 0.6%
Fe_2O_3 = 12.4%

CaO = 3.2%
MgO = 1.3%
K_2O = 3.2%
Na_2O = 1.5%

ASH SOFTENING TEMPERATURES (°C)

T_1 = 1200 (1100-1400)
T_2 = 1340 (1150-1450)
T_3 = 1380 (1200-1480)

SECONDARY FUEL - NATURAL GAS

START-UP FUEL - FUEL OIL

3. HEAT BALANCE AND FUEL BURNING RATE

THERMAL BOILER EFFICIENCY = 89.7%
FULL FUEL BURNED 181.5×10^3 KG/HR.
DESIGN FUEL RATE 180.6×10^3 KG/HR.

4. FURNACE CHARACTERISTICS

HEAT RELEASE/NET FURNACE VOLUME = 134.1×10^3 $KCAL/M^3$
HEAT RELEASE/AREA = 4.73×10^6 $KCAL/M^2$ HR.

FURNACE OUTLET TEMPERATURE = 1218°C

(Continued)

Table 2-1. Continued

5.	**AIR BALANCE AND EXCESS AIR**	
	FURNACE OUTLET EXCESS AIR	1.2
	FURNACE AIR INFILTRATION	0.05
	P.C. SYSTEM AIR INFILTRATION	0.036
	PORTION OF PRIMARY AIR TO THE FURNACE	0.228
	PORTION OF SECONDARY AIR TO FURNACE	0.922
	RECIRCULATION GAS PORTION IN THE DRYING AGENT	0.23
	OXYGEN CONTENT IN THE DRYING AGENT AT MILL FAN	16.5%
6.	**AIR AND DRYING AGENT FLOW RATES**	
	DRYING HOT AIR (350°C)	72.3 M^3/SEC
	RECIRC. GAS FOR DRYING (390°C)	15.7 M^3/SEC
	DRYING AGENT AFTER MILL FAN (80°C)	100 M^3/SEC
	P.C. DUCT TO BURNERS	68.4 M^3/SEC
	P.C. DUMP DUCT	16 M^3/SEC
	SECONDARY TO BURNERS (359°C)	448 M^3/SEC
7.	**P.C. PREPARATION SYSTEM**	
	DRUM BALL MILLS	
	TYPE 370/850	2 PER BOILER
	CAPACITY	80 T/HR
	FINENESS	R = 30% ON 90 MICRON R = 5% ON 200 MICRON
	MOISTURE	2% AFTER PULVERIZER
8.	**BURNERS (MODIFIED)**	
	TYPE: ONCE THRU, SWIRLING	16 EACH

(Continued)

Table 2-1. Continued

FURNACE INLET VELOCITIES

PRIMARY AIR (ONCE THRU)	20 M/SEC
SECONDARY AIR (SWIRLING)	34 M/SEC
DUMP NOZZLE	40 M/SEC

analysis, and power plant fuel utilization information were also made available to the U.S. side. This information is summarized in Table 2-2.

Additional design information was relayed to the U.S. side in the form of over forty (40) drawings; these drawings describe the boiler's natural gas systems, flue gas recirculation system, refractory and casing arrangements, ductwork arrangements, steam and water sub-systems, burner arrangements, overall process schematics, and plan and elevational views of the boiler. Furnace gas temperature profiles were also included. This information has been summarized in Table 2-3. The drawings themselves have not been included in the report.

In addition to the above information, the Soviet side graciously allowed the U.S. side to photograph boiler externals during the plant visit. Over 100 photographs were taken at all assessable boiler elevations. These photographs were extensively referred to as the preliminary reburn system design evolved; the photographs were used to confirm that the boiler modifications identified in the preliminary design could be implemented without any major relocation of boiler externals.

Table 2-2. Typical Operating Characteristics of the Ladyzhinskaya Steam Generator

Typical unit turndown (all burner's in service)	300MWe -> 210MWe
Plant elevation	208 meters above sea level
Reburn fuel options: 1 - 100% gas 2 - 100% coal 3 - Dual fuel (gas/coal)	
Typical carbon loss	≤ 1.0% carbon in flyash
ESP's per boiler	2
Mills per boiler	2
Ash collection	Wet bottom - slag hydraulically transported to landfill 12 kilometers distant
Ash split	30% slag 70% flyash
Baseline NO_x levels: 2 conflicting tests - (original) 1300 milligrams/NM^3 @ 6% O_2 (no primary swirl, decreased coal grade and temp) 650 milligrams/NM^3 @ 6% O_2	

(Continued)

Table 2-2. Continued

Typical O_2 level	3.5% @ furnace outlet 4.0% @ after economizer
Typical CO level	0.00
Flue gas quantity	18% of total 13-14% upper 4 - 5% lower (dump burners)
Primary Air	$O_2 < 16\%$ @ 70°F
Secondary Air	$O_2 = 21\%$ @ 370° - 400° F

Natural Gas Analysis: (dry)

Q - 8107 kcal/M^3

CH_4 - 90, 9%
C_2H_6 - 3.41%
C_3H_8 - 0.91%
C_4H_{10} - 0.7%
N_2 - 4.11%
CO_2 - 0.5%
Normal Gas Water Content 3%

- Unit can make MCR on Natural Gas

- Summer operation	70% gas 30% coal
Winter operation	70% coal 30% gas

During cold weather (<12°C) no gas available for boiler

- Heavy oil start-up fuel

Table 2-3. Listing of Drawings and Supplemental Design Information on the Ladyzhinskaya Steam Generator Supplied by the Soviets

MAJOR GROUP	DRAWING NO.	SUBTITLE
Natural Gas System	7033-2-TT-I	Natural Gas Supply System For Ladyzhin GRES - Main Building - Boiler's Natural Gas Ducts, Installation, Assembly Drwg.
	7033-2-TT-II	Same as above
	7033-2-TT-III	Same as above (with cross-sections II-II, III-III, IV-IV, V-V)
Flue Gas Recirculation	1019	Boiler backpass covering flue gas ducts. Inlet duct modification for units 4 and 6.
	1305	Flue gas recirculation discharge duct, unit #5
	1306	Flue gas recirculation discharge duct, unit #5 cross sections "A-A" and "T-F" (6-6)
	1381	Injection of dust laden air into the furnace

(Continued)

Table 2-3. Continued

MAJOR GROUP	DRAWING NO.	SUBTITLE
REFRACTORY AND CASING	K474848	BOILER REFRACTORY ARRANGEMENT (SIDE ELEVATION VIEW: VIEW ALONG THE UNIT'S LONG SIDE)
	K474849	BOILER REFRACTORY ARRANGEMENT (SIDE ELEVATION VIEW: VIEW ALONG THE UNIT'S SHORT SIDE
	K474852	SIDE WALL REFRACTORY ARRANGEMENT LOWER FURNACE RADIATION SECTION
	K474853P	REFRACTORY ARRANGEMENT OF THE FRONT WALL OF THE FURNACE, INTERMEDIATE RADIATION SECTION I
	K474854P	FURNACE'S INTERMEDIATE RADIATION SECTION I SIDE WALL REFRACTORY ARRANGEMENT
	K474855P	FURNACE INTERMEDIATE RADIATION SECTION II FRONT (BACK) WALL REFRACTORY ARRANGEMENT

(Continued)

Table 2-3. Continued

MAJOR GROUP	DRAWING NO.	SUBTITLE
REFRACTORY AND CASING (CONT.)	K474856P	FURNACE INTERMEDIATE RADIATION SECTION II, SIDE WALL REFRACTORY ARRANGEMENT
	K474920P	SIDE WALL REFRACTORY DETAILS, INTERMEDIATE RADIATION FURNACE SECTIONS I AND II
	K590946	INTERMEDIATE RADIATION SECTION - GENERAL VIEW
	K335687P	WATERWALL #14, FURNACE LOWER RADIATION SECTION
	K335686P	WATERWALL #13 FURNACE'S LOWER RADIATION SECTION
	K335685P	WATERWALL #12 FURNACE'S LOWER RADIATION SECTION
	K335684P	WATERWALL #11 FURNACE'S LOWER RADIATION SECTION
	K335683P	WATERWALL #10

(Continued)

Table 2-3. Continued

MAJOR GROUP	DRAWING NO.	SUBTITLE
REFRACTORY AND CASING (CONT.)	242357	P.C. DUCTS TO BURNERS, GENERAL VIEWS CROSS-SECTIONS "B-B", "T-T" (6-6), "D-D", I-E, (J-J) GENERATOR #4
	242358	P.C. DUCTS TO BURNERS, GENERAL VIEWS STEAM GENERATOR #4
	239600(A)	P.C. DUCTS TO BURNERS, GENERAL VIEWS, TOP VIEW, 3-3 STEAM GENERATOR #4
	239601(A)	P.C. DUCTS TO BURNERS, GENERAL VIEWS, CROSS-SECTIONS, STEAM GENERATOR #4
	239602(A)	P.C. DUCTS TO BURNERS, GENERAL VIEWS, CROSS-SECTIONS, STEAM GENERATOR #4
	239603(A)	P.C. DUCTS TO BURNERS, GENERAL VIEWS, CROSS-SECTIONS, STEAM GENERATOR #4

(Continued)

Table 2-3. Continued

MAJOR GROUP	DRAWING NO.	SUBTITLE
REFRACTORY AND CASING (CONT.)	239604	P.C. DUCTS TO BURNERS, GENERAL VIEW, VIEW "A" STEAM GENERATOR #1
STEAM AND WATER LINES	K592162	BOILERS STEAM AND WATER LINES
	K592163	BOILER STEAM AND WATER LINES (FRONT ELEVATOR VIEW, AND CROSS SECTION ALONG THE SHORT SIDE OF UNIT)
	K592164	BOILER'S STEAM AND WATER LINES (PLAN VIEW AT DIFFERENT ELEVATIONS)
GAS RECIRCULATION DIAGRAM	1050	-
GENERAL	236850	BURNER INSTALLATION - PLAN VIEW
	236849	BURNER INSTALLATION - ELEVATION VIEW
	H5913 77	FURNACE LOWER RADIANT SECTION (LRS)

(Continued)

Table 2-3. Continued

MAJOR GROUP	DRAWING NO.	SUBTITLE
GENERAL (CONT.)	16672	OVERALL PROCESS SCHEMATIC
	236851	BURNER AIR DUCTS (PLAN VIEW)
	N201154	PLAN VIEW
	201153	FRONT ELEVATION HALF VIEW
	201152	ELEVATIONAL - SIDE VIEW
	HANDWRITTEN	ELEVATIONAL FURNACE GAS TEMP PLOTS

SECTION 3

SYSTEM PROCESS DESIGN

The system process design was initiated by establishing overall reburn process objectives. Overall process objectives for the reburn system were:

(1) To meet key design criteria for effective NO_x reduction while minimizing any impact on normal boiler operation.

(2) To incorporate operational flexibility within the design to permit optimized host unit performance.

A list of key design criteria commensurate with the overall design objectives for the reburn system was initially established. The criteria consists of theoretical criteria for effective NO_x reduction and practical, commercial considerations for reburn system design, installation, and operation.

Key design criteria for the reburn zone were determined to be:

- Inject reburn fuel into as high a temperature zone as possible.
- Maintain average stoichiometry between 0.90 and 0.99.
- A small amount of O_2 should be present to promote formation of OH and H radicals.
- Maintain a minimum furnace gas residence time of 0.5 seconds.
- Maximize entrainment, mixing, and dispersion of reburn fuel.

- Avoid direct fuel impingement on boiler walls.
- Minimize the number of required boiler penetrations.
- Locate fuel injection nozzles to minimize boiler/structural steel modifications.
- Provide for maximum flexibility of reburn fuel jet direction and flow rates.
- Provide fuel flow rate control system with automatic load following capability.
- Provide safeguards for fail-safe operation.

The first five criteria, above, deal with theoretical considerations while the last six deal with practical, commercial considerations.

Injection of reburn fuel into a high temperature zone enhances NO_x reduction by favoring higher chemical reaction rates; however, reburn fuel should not be injected before the bulk of the primary fuel has burned to completion. If injected too early in a coal fired boiler, natural gas, as the reburn fuel, would preferentially burn before the coal char particles have burned to completion. This could increase the possibility for unburned carbon while, additionally, not permitting all the char bound nitrogen to be released prior to the reburn zone.

A stoichiometry in the range of 0.90 to 0.99 has been found to represent a reasonable balance between achieving a desirable stoichiometry from the standpoint of NO_x reduction chemistry and a stoichiometry that will not exacerbate ash deposition and/or boiler tube wastage. Though the reaction kinetics for NO_x reduction in the reburn zone are quite fast, requiring on the order of 0.1 second, the bulk of the residence time in the reburn zone is required to achieve good mixing of the reburn fuel with the bulk furnace gases. The naturally occurring small amounts of oxygen in the bulk furnace gas entering the reburn zone, along with that in the recirculated flue gas, which is used to carry and mix the natural gas, are sufficient to promote the desired formation of OH and H radicals. Effective and rapid mixing of reburn fuel ensures that all NO_x entering the reburn zone will contact the intermediate nitrogen-containing species so that maximum NO_x reduction is possible. Effective mixing must be achieved in such a way that there is no direct fuel impingement on boiler walls. This impingement could exacerbate tube wastage or iron-related ash deposition by creating low local stoichiometries. Effective mixing would eliminate extremes between highly oxidizing and highly reducing atmospheres which could promulgate corrosion.

Other practical considerations involve minimizing the number of boiler penetrations and the avoidance of unnecessarily costly boiler modifications relative to the number and placement of reburn fuel injectors. The number and placement of reburn fuel injectors must not create thermal or structural boiler problems.

The reburn fuel injection system should have sufficient flexibility to permit on-line adjustment to maintain optimum mixing as a function of boiler operational variables, such as load changes, that could alter gas flow patterns within the reburn zone. Since the amount of reburn fuel required will likely change as a function of boiler load, a control system should be provided which will provide automatic load following capability. The reburn fuel control system should also have permissives which must be satisfied to ensure its safe operation.

Key design criteria for the burnout zone were determined to be:

- Inject burnout air in as low a temperature zone as possible commensurate with obtaining fuel burnout before entering the first convective surface.
- Provide for rapid mixing of air to minimize pockets of unburned fuel.
- Avoid direct air impingement on furnace walls.
- Minimize final excess oxygen commensurate with obtaining good fuel burnout.
- Maintain a minimum furnace gas residence time of 0.6 seconds.
- Minimize the number of required boiler penetrations commensurate with obtaining good mixing.
- Locate burnout air injectors to minimize boiler structural modifications while providing good mixing.
- Provide for maximum flexibility of air jet direction and flow.
- Provide an air flow rate control system with automatic load following capability.
- Provide safeguards for fail-safe operation.

For the burnout zone, unlike the reburn zone, air should be injected in as low a temperature gas as possible to prevent the reformation of NO_x.

However, lower temperatures could prevent complete burnout of the uncombusted fuel which leaves the reburn zone, and a balance must be struck between the dual objectives of minimizing NO_x reformation and complete combustible burnout.

Rapid and thorough mixing in the burnout zone is necessary. Although the reaction between fuel and oxygen is quite rapid, the bulk of the recommended minimum 0.6 second residence time is needed to achieve effective mixing rather than for combustion reaction time, per se. Direct impingement of air on furnace walls should be avoided, more for reasons of preventing local temperature increases than for any concern about the presence of an oxidizing atmosphere. The amount of air should be just sufficient to achieve desired fuel burnout; an overabundance of excess air will contribute to dry gas losses and boiler efficiency and will increase the potential for NO_x reformation in the burnout zone. The rationale for employment of the practically oriented burnout zone design criteria is basically the same as that presented earlier for the reburn zone.

In addition to the above design criteria, the Ladyzhinskaya plant personnel requested that the preliminary reburn system design also meet the following criteria:

1. Reburn system operation cannot affect slag tapping.
2. Temperature growth (when reburn system operating) must be within tube design limits.

3. Slagging/fouling characteristics should not change.

With the above in mind, C-E initiated reburn system design for the Ladyzhinskaya unit. An intergral part of the design process was to perform mass balance and combustion calculations on the overall process. Process flows used for this calculation (based on data provided by the Soviet side), are shown in Figure 3-1. Using this information, the Soviet coal analysis, an estimate of gas recirculation mass flow (FGR) necessary for the reburn fuel injectors, and furnace dimensions and gas temperatures, a proprietary Combustion Engineering, Inc. computer code was employed to calculate stoichiometric ratio's and gas residence times in boiler zone 1 (the furnace bottom to the reburn zone start), zone 2 (the reburn fuel injection position to the burnout air injection position or reburn zone) and zone 3 (the burnout air injection position to the horizontal furnace outlet plane, or burnout zone). Estimates for the reburn fuel and burnout air injection position were input into the code and then iteratively adjusted to:

1. Achieve a reburn zone (zone 2) stoichiometry between 0.9 - 0.99.
2. Achieve a reburn zone gas residence time of greater than 0.5 seconds.
3. Achieve a burnout zone (zone 3) stoichiometry similar to that of zone 1.
4. Achieve a burnout zone gas residence time of greater than 0.6 seconds.

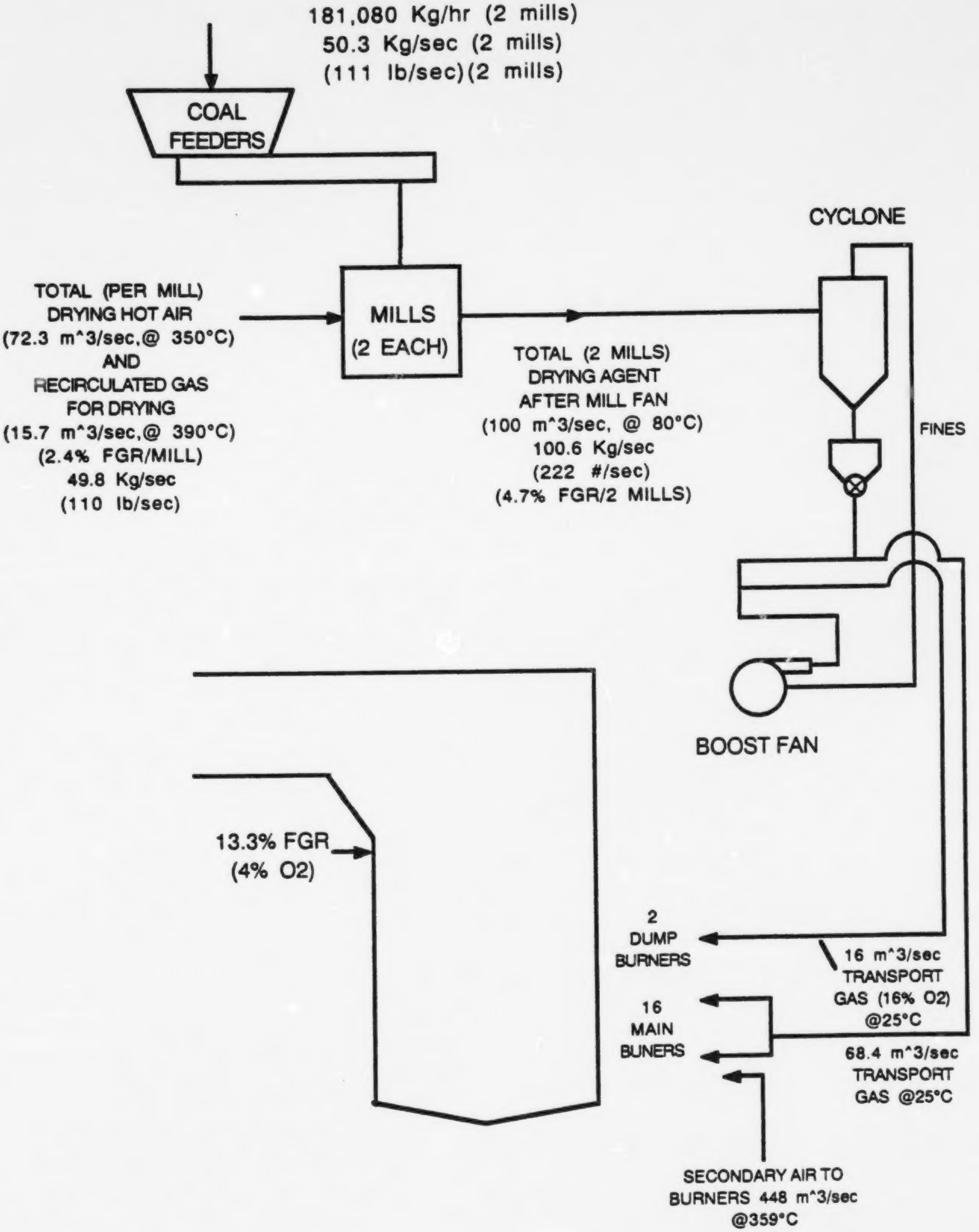

181,080 Kg/hr (2 mills)
50.3 Kg/sec (2 mills)
(111 lb/sec)(2 mills)
COAL FEEDERS
MILLS (2 EACH)
CYCLONE
TOTAL (PER MILL) DRYING HOT AIR (72.3 m^3/sec,@ 350°C) AND RECIRCULATED GAS FOR DRYING (15.7 m^3/sec,@ 390°C) (2.4% FGR/MILL) 49.8 Kg/sec (110 lb/sec)
TOTAL (2 MILLS) DRYING AGENT AFTER MILL FAN (100 m^3/sec, @ 80°C) 100.6 Kg/sec (222 #/sec) (4.7% FGR/2 MILLS)
FINES
BOOST FAN
13.3% FGR (4% O2)
2 DUMP BURNERS
16 m^3/sec TRANSPORT GAS (16% O2) @25°C
16 MAIN BUNERS
68.4 m^3/sec TRANSPORT GAS @25°C
SECONDARY AIR TO BURNERS 448 m^3/sec @359°C

Figure 3-1. Summary of Existing Process Flows At The Ladyzhinskaya Steam Generating Unit

SCHEM1A

This program calculates the flow rates of fuel, air, and FGR entering the main burner zone, reburn zone, and burnout air zone, and calculates the furnace gas compositions leaving each zone. Furnace gas residence times in each zone are also determined based on calculated furnace gas flows, zone volumes determined from blueprints, and assumed average gas temperatures in each zone. The average gas temperatures (supplied by the Soviet side) are:

Zone 1) 2675°F (1468°C)
Zone 2) 2425°F (1330°C)
Zone 3) 2275°F (1246°C)

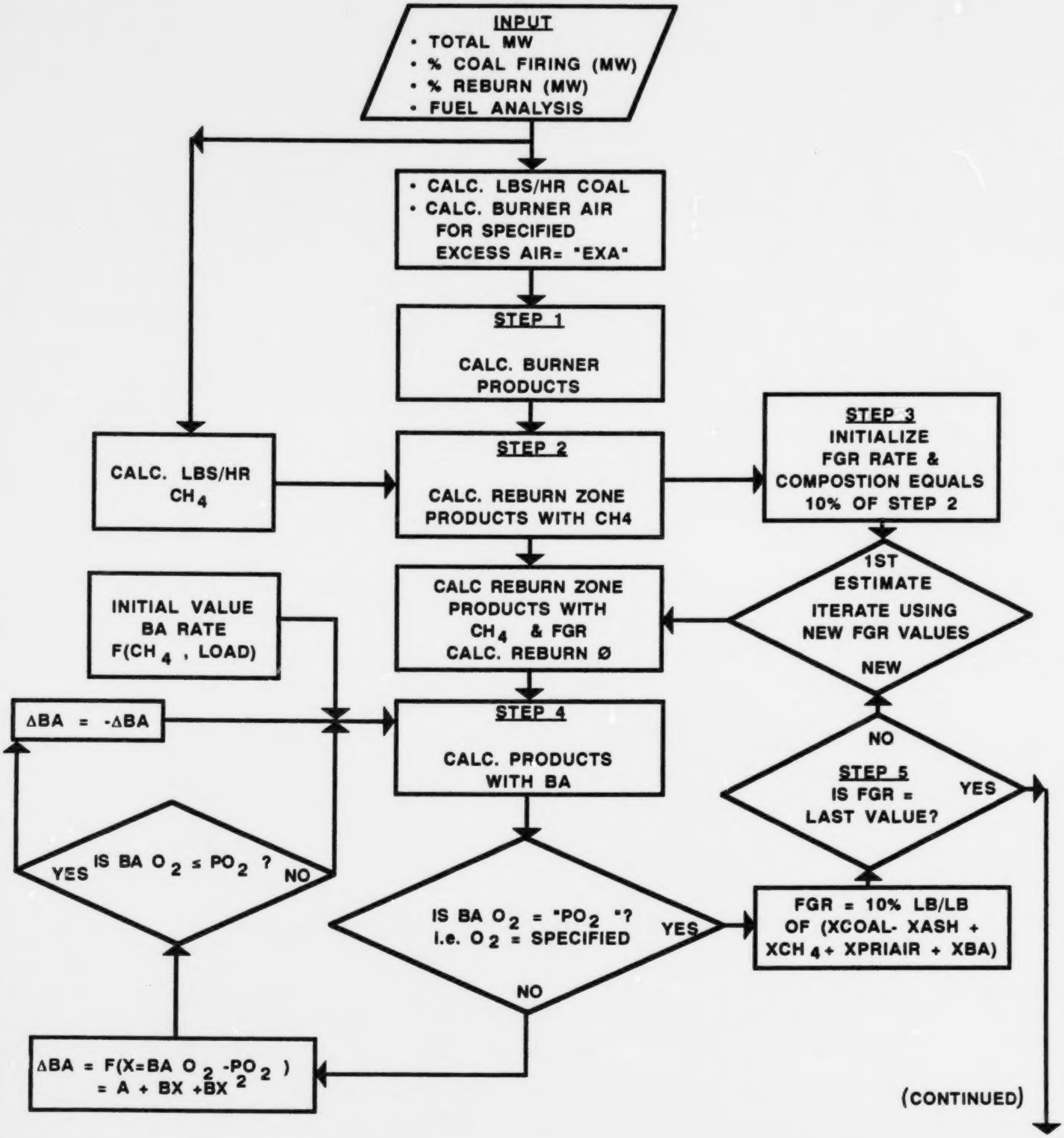
Lastly, reburn zone stoichiometry is calculated as:

$$\text{o Reburn Stoichiometry} = \frac{\text{Total } O_2 \text{ in from mainburners + FGR (lbs)}}{\text{Total } O_2 \text{ required for coal} + CH_4 \text{ (lbs)}}$$

Assuming:

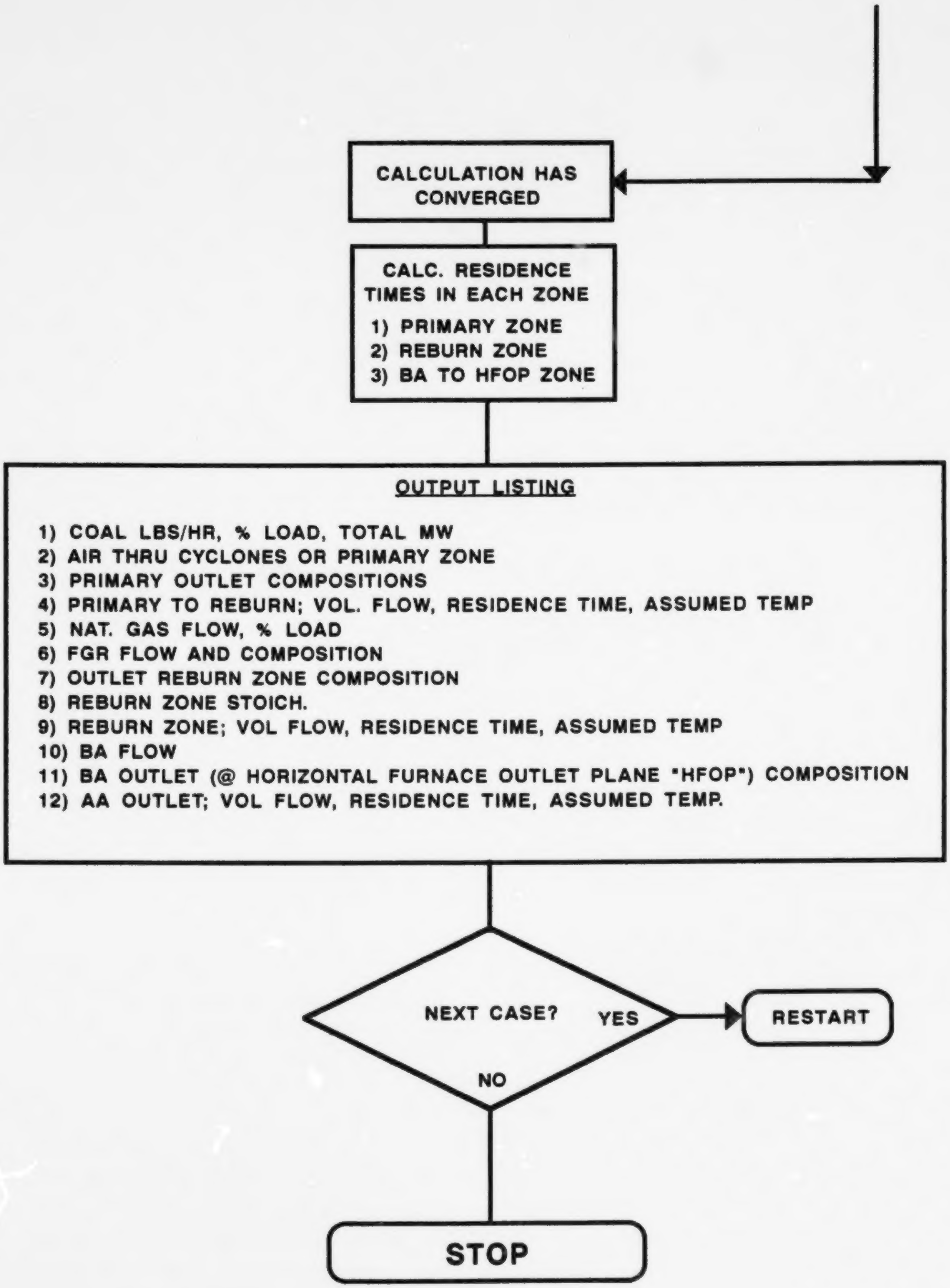
1. The main burner fuel has essentially been completely combusted.
2. The reburn fuel, natural gas, is principally comprised of methane (CH_4).

The overall calculation (shown in Figures 3-2 and 3-3) is iterative because of the flue gas recirculation. For the computation an initial


INPUT
• TOTAL MW
• % COAL FIRING (MW)
• % REBURN (MW)
• FUEL ANALYSIS
• CALC. LBS/HR COAL
• CALC. BURNER AIR FOR SPECIFIED EXCESS AIR= "EXA"
STEP 1
CALC. BURNER PRODUCTS
CALC. LBS/HR CH4
STEP 2
CALC. REBURN ZONE PRODUCTS WITH CH4
STEP 3
INITIALIZE FGR RATE & COMPOSTION EQUALS 10% OF STEP 2
1ST ESTIMATE
ITERATE USING NEW FGR VALUES
NEW
INITIAL VALUE BA RATE F(CH4 , LOAD)
CALC REBURN ZONE PRODUCTS WITH CH4 & FGR CALC. REBURN Ø
ΔBA = -ΔBA
STEP 4
CALC. PRODUCTS WITH BA
NO
STEP 5
IS FGR = LAST VALUE?
YES
YES
IS BA O2 ≤ PO2 ?
NO
IS BA O2 = "PO2 "? i.e. O2 = SPECIFIED
YES
NO
FGR = 10% LB/LB OF (XCOAL- XASH + XCH4+ XPRIAIR + XBA)
ΔBA = F(X=BA O2 -PO2) = A + BX +BX2
(CONTINUED)

BA = BURNOUT AIR

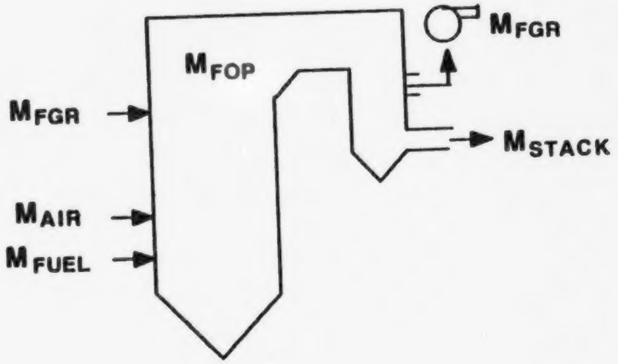
Figure 3-2. Flow Chart of Reburn Process Computer Code


CALCULATION HAS CONVERGED
CALC. RESIDENCE TIMES IN EACH ZONE
1) PRIMARY ZONE
2) REBURN ZONE
3) BA TO HFOP ZONE
OUTPUT LISTING
1) COAL LBS/HR, % LOAD, TOTAL MW
2) AIR THRU CYCLONES OR PRIMARY ZONE
3) PRIMARY OUTLET COMPOSITIONS
4) PRIMARY TO REBURN; VOL. FLOW, RESIDENCE TIME, ASSUMED TEMP
5) NAT. GAS FLOW, % LOAD
6) FGR FLOW AND COMPOSITION
7) OUTLET REBURN ZONE COMPOSITION
8) REBURN ZONE STOICH.
9) REBURN ZONE; VOL FLOW, RESIDENCE TIME, ASSUMED TEMP
10) BA FLOW
11) BA OUTLET (@ HORIZONTAL FURNACE OUTLET PLANE "HFOP") COMPOSITION
12) AA OUTLET; VOL FLOW, RESIDENCE TIME, ASSUMED TEMP.
NEXT CASE?
YES
RESTART
NO
STOP

BA = BURNOUT AIR

Figure 3-2. continued

X% FLUE GAS RECIRCULATION = X% OF STACK FLUE GAS FLOW
= X% OF SUM OF FUEL AND AIR ENTERING THE FURNACE


M_{FGR}
M_{FOP}
M_{FGR}
M_{STACK}
M_{AIR}
M_{FUEL}

$$M_{AIR} + M_{FUEL} = M_{STACK}$$

$$M_{FGR} = \frac{X\%\ FGR}{100}(M_{STACK}) = \frac{X\%\ FGR}{100}(M_{AIR} + M_{FUEL})$$

$$M_{FOP} = M_{FGR} + M_{AIR} + M_{FUEL} = M_{FGR} + M_{STACK} = \left(\frac{X\%\ FGR}{100} + 1\right) M_{STACK}$$

Figure 3-3. Definition of FGR Flow

FGR flow must be assumed so that the products leaving the reburn zone can be calculated. Then burnout air is added to achieve the desired outlet 0_2 level.

Once convergence on the burnout air outlet 0_2 level is obtained, the FGR flow rate and composition can be calculated. If the mass flow of FGR differs from the value used on the last iteration then the new FGR flows and compositions are used to enter the reburn zone and the calculation iterates again. On each iteration of FGR, the burnout air flows must also be recalculated iteratively. Once convergence is obtained on FGR, the calculation is complete. Furnace gas residence times in each zone are then calculated and a data output listing is made.

The final design case mode inputs for the Ladyzhinskaya preliminary reburn system design has been shown in Figure 3-4. A summary of the process design calculations for the final design case has been shown in Figures 3-5, 6, and 7.

A side elevational view showing the final elevations for the reburn injectors (20.3M) and the burnout air injectors (29.2M) has been shown in Figure 3-8.

Gas residence times in each of the three boiler zones have been shown in Figure 3-9. The main burner zone residence time (assuming uniform furnace gas flow) equals 1.59 sec., gas residence time in the reburn zone equals 1.00 sec., and gas residence time in the burnout zone equals 0.96 sec. at the correct stoichiometric ratios.

DESIGN CASE FOR LADYZHINSKAYA REBURN SYSTEM
(COAL MAIN FUEL/NATURAL GAS REBURN FUEL)

- Load - 300 MWe
- % Total Heat Input As Reburn Fuel - 20%
- O_2 at Furnace Outlet - 3.5%
- Coal Analysis
    - Carbon - 40.1
    - Hydrogen - 3.0
    - Nitrogen - 0.8
    - Sulfur - 2.0
    - Oxygen - 6.9
    - Ash - 35.2
    - Moisture - 12.0
- % By Weight GR - 4.7%
  (Primary Zone)
  (Total)
- % By Weight GR - 14.7%
  (Reburn Zone)
  (Total)

(Continued)

Figure 3-4. Computer Code Input For Final Design Case

- % By Weight GR - 18%
  - (Burnout Zone)
    - (Total)
- Reburn Fuel Injection Elevation - 20.3M
- Burnout Air Injection Elevation - 29.2M
- Average Gas Temps -
  - Primary Zone - 2675°F
  - Reburn Zone - 2425°F
  - Burnout Zone - 2275°F
- Furnace Plan Areas
  - Primary Zone - $150M^2$
  - Reburn Zone - $150M^2$
  - Burnout Zone - $150M^2$
- Furnace Volumes
  - Primary Zone - $2160M^3$
  - Reburn Zone - $1335M^3$
  - Burnout Zone - $1537M^3$

Figure 3-4. Continued

Total Boiler Load - 300MWe
Percent Heat Release As Reburn Fuel - 20%
Coal Firing Rate (lbs/hr) - 320066
Combustion Air Flow Thru Burners - 2034337
Gas Residence Time (Zone 1) (Sec) 1.59

Volume Flow (Ft^3/sec) wet gases
out of primary zone - 48004

Ash Flow Rate (lbs/hr) - 90131

Gas Composition at Outlet of Primary Zone (% by Volume Dry)
- CO_2 = 15.59
O_2 = 3.12
N_2 = 81.00
SO_2 = 0.29
H_2O = 0.0

Gas Composition at Outlet of Primary Zone (% by Volume Wet)
- CO_2 = 14.16
O_2 = 2.84
N_2 = 73.56
SO_2 = 0.26
H_2O = 9.18

* Does not account for 4.7% FGR in Zone 1

Figure 3-5. Design Case Reburn Process Calculation Results For Boiler Zone 1, The Main Burner Zone

REBURN HEAT INPUT (20% OF TOTAL) (LBS/HR)	24314
PERCENT BY WEIGHT FGR	14.7%
FLUE GAS RECIRCULATION (LBS/HR)	410407
GAS RESIDENCE TIME (ZONE 2) (SEC)	1.00
VOLUME FLOW (FT^3/SEC) WET GASES OUT OF REBURN ZONE	47084
REBURN ZONE STOICHIOMETRY	0.97
ASH FLOW RATE (LB/HR)	102965
GAS COMPOSITIONS AT OUTLET OF REBURN ZONE (% BY VOLUME DRY)	CO_2 = 17.20 O_2 = .00 N_2 = 82.22 SO_2 = 0.286 H_2O = 0 .00 CH_4 = 0.29
GAS COMPOSITIONS AT OUTLET OF REBURN ZONE (% BY VOLUME SET)	CO_2 = 17.11 O_2 = 0.00 N_2 = 81.78 SO_2 = 0.285 H_2O = 0.53 CH_4 = 0.29

Figure 3-6. Design Case Reburn Process Calculation Results For Boiler Zone 2, The Reburn Zone

BURNOUT AIR (LBS/HR)	- 525829
PERCENT BY WEIGHT FGR	- 18%
GAS RESIDENCE TIME (SEC) (ZONE 3)	- 0.96
VOLUME FLOW (FT^3/SEC) WET GASES OUT OF FURNACE OUTLET	- 56258
ASH FLOW RATE (LB/HR)	- 105847
GAS COMPOSITION AT FURNACE OUTLET (% BY VOLUME DRY)	CO_2 = 14.33 O_2 = 3.42 N_2 = 82.02 SO_2 = 0.235 H_2O = 0.0
GAS COMPOSITION AT FURNACE OUTLET (% BY VOLUME WET)	- CO_2 = 14.20 O_2 = 3.39 N_2 = 81.29 SO_2 = 0.233 H_2O = 0.88

Figure 3-7 Design Case Reburn Process Calculation Results For Boiler Zone 3, The Burnout Zone

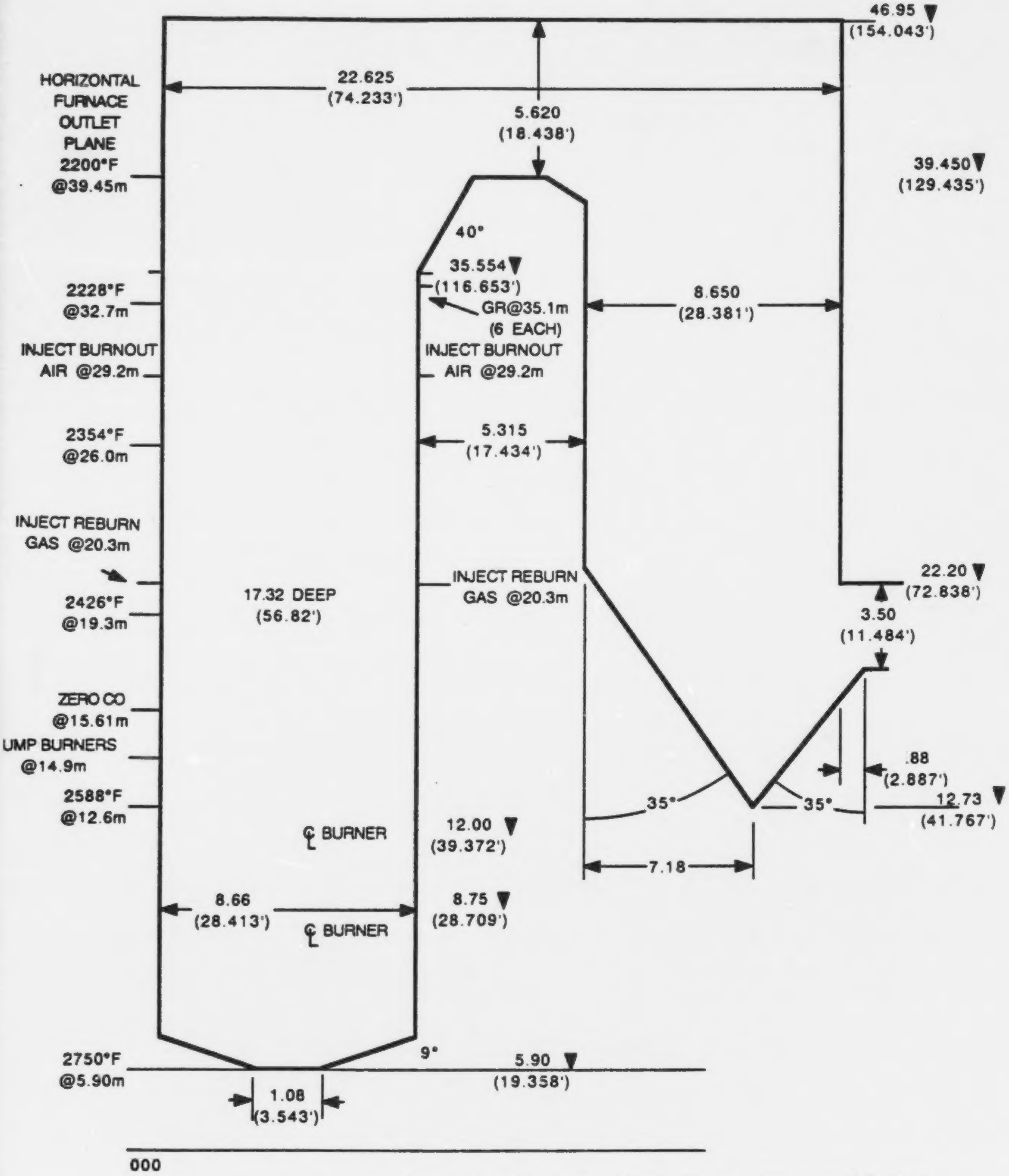

46.95
(154.043')
HORIZONTAL FURNACE OUTLET PLANE 2200°F @39.45m
22.625
(74.233')
5.620
(18.438')
39.450
(129.435')
40°
35.554
(116.653')
2228°F @32.7m
GR@35.1m (6 EACH)
8.650
(28.381')
INJECT BURNOUT AIR @29.2m
INJECT BURNOUT AIR @29.2m
5.315
(17.434')
2354°F @26.0m
INJECT REBURN GAS @20.3m
22.20
(72.838')
INJECT REBURN GAS @20.3m
17.32 DEEP
(56.82')
2426°F @19.3m
3.50
(11.484')
ZERO CO @15.61m
UMP BURNERS @14.9m
.88
(2.887')
2588°F @12.6m
35°
35°
12.73
(41.767')
℄ BURNER
12.00
(39.372')
7.18
8.66
(28.413')
8.75
(28.709')
℄ BURNER
9°
2750°F @5.90m
5.90
(19.358')
1.08
(3.543')
000

Figure 3-8. Side View Schematic of Ladyzhinskaya Steam Generator Showing Preliminary Reburn Fuel and Burnout air Injector Locations

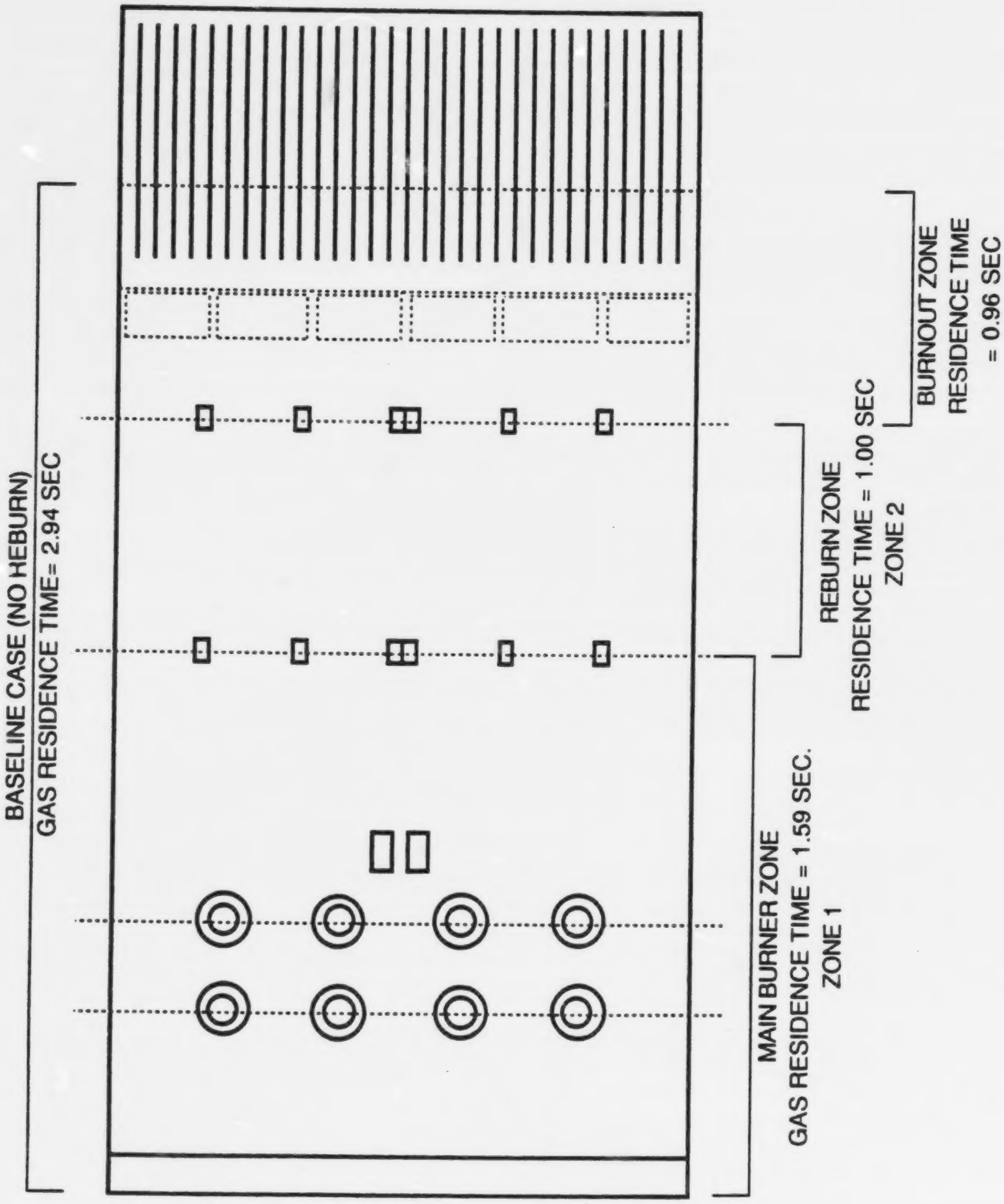

BASELINE CASE (NO REBURN)
GAS RESIDENCE TIME= 2.94 SEC
MAIN BURNER ZONE
GAS RESIDENCE TIME = 1.59 SEC.
ZONE 1
REBURN ZONE
RESIDENCE TIME = 1.00 SEC
ZONE 2
BURNOUT ZONE
RESIDENCE TIME
= 0.96 SEC
ZONE 3

Figure 3-9. Front/Rear Elevational Schematic Presenting Preliminary Reburn Fuel and Burnout Air Injector Locations and Zone Residence Times

In conclusion, process calculations identified main fuel, reburn fuel, burnout air, and recirculated flue gas flows within boiler to achieve design criteria stoichiometry and optimum injection elevations were identified to achieve design criteria residence time(s). The elevational locations for the reburn fuel and burnout air injectors were studied in a physical flow model of the Ladyzhinskaya boiler; these studies are reviewed elsewhere in this report.

SECTION 4

PHYSICAL FLOW MODELING

TASK DESCRIPTION

Isothermal flow modeling studies were conducted as part of this program to develop and evaluate reburn fuel and burnout air injection locations and methods for the 300 M.W. coal fired boilers of the Ladyzhinskaya Power Station. The flow modeling used techniques developed during C-E's previous EPA sponsored reburn program where a cold flow air model was used to predict the penetration and mixing performance of methane/FGR reburn fuel jets and burnout air jets with hot furnace gasses (9). Baseline furnace aerodynamics were evaluated as well as the performance of a number of candidate reburn systems configurations. From the information obtained, recommendations for the number, location and operating parameters of the reburn fuel and burnout air systems were made.

The isothermal flow modeling study was comprised of five subtasks. The objectives of these tasks were to:

1. Design and fabricate a 1/16 scale cold flow model of the Ladyzhinskaya boiler.

2. Perform qualitative evaluation of the boiler's baseline aerodynamic flow field.

3. Identify candidate reburn fuel and burnout air injection location/method combinations which provide effective penetration and dispersion within their respective zones of the furnace.

4. Screen the proposed reburn fuel and burnout air injection systems through qualitative evaluation of their penetration and dispersion performance. Specifically;

   - Maximize entrainment, mixing and dispersion of the injected material.

   - Provide for the early dispersion of the injected material so as to maximize residence time within the respective furnace zones.

   - Avoid direct impingement of injected material on furnace walls.

   - Minimize the impact of system installation on furnace operation by minimizing the number of injection locations.

   - Maximize overall system flexibility.

5. Recommend those injection configurations and operational parameters which meet the criteria specified under subtask 4.

The following section discusses the aerodynamic test facilities, the tests performed, and the conclusions and recommendations of the isothermal flow modeling studies.

DESCRIPTION OF FLOW MODELING FACILITIES

The test program was performed at Combustion Engineering's Kreisinger Development Laboratory in Windsor, Connecticut. Figure 4-1 presents a general view of KDL's Main Cold Flow Modeling Test Facilities. Physical flow modeling has been proven to be an accurate and cost effective approach for improving and developing many processes and components associated with modern steam generation systems. C-E's Mechanical Systems Engineering Group operates flow modeling facilities capable of simulating and evaluating flow models of either two or three dimensional design.

The Ladyzhinskaya Furnace Flow Model

A 1/16 scale geometrically similar isothermal flow model of the Ladyzhinskaya boiler was fabricated. This model as shown in Figure 4-2 encompasses the boiler from the furnace hopper bottom to the inlet to the economizer section. This flow model was built primarily of plexiglas with sheet steel used for the main burners and heat transfer surfaces.

The boiler's superheater section was fabricated from sheet steel. The total number of sections and axial free gas areas of these sections were chosen based on the calculated axial and transverse pressure drop coefficients of the prototype Ladyzhinskaya steam generator heat transfer sections. The required spacings were determined using curves developed in the laboratory's wind tunnel, for in-line tube banks simulated by plates. Every effort was made to simulate, as closely as possible, the number of in-line banks found

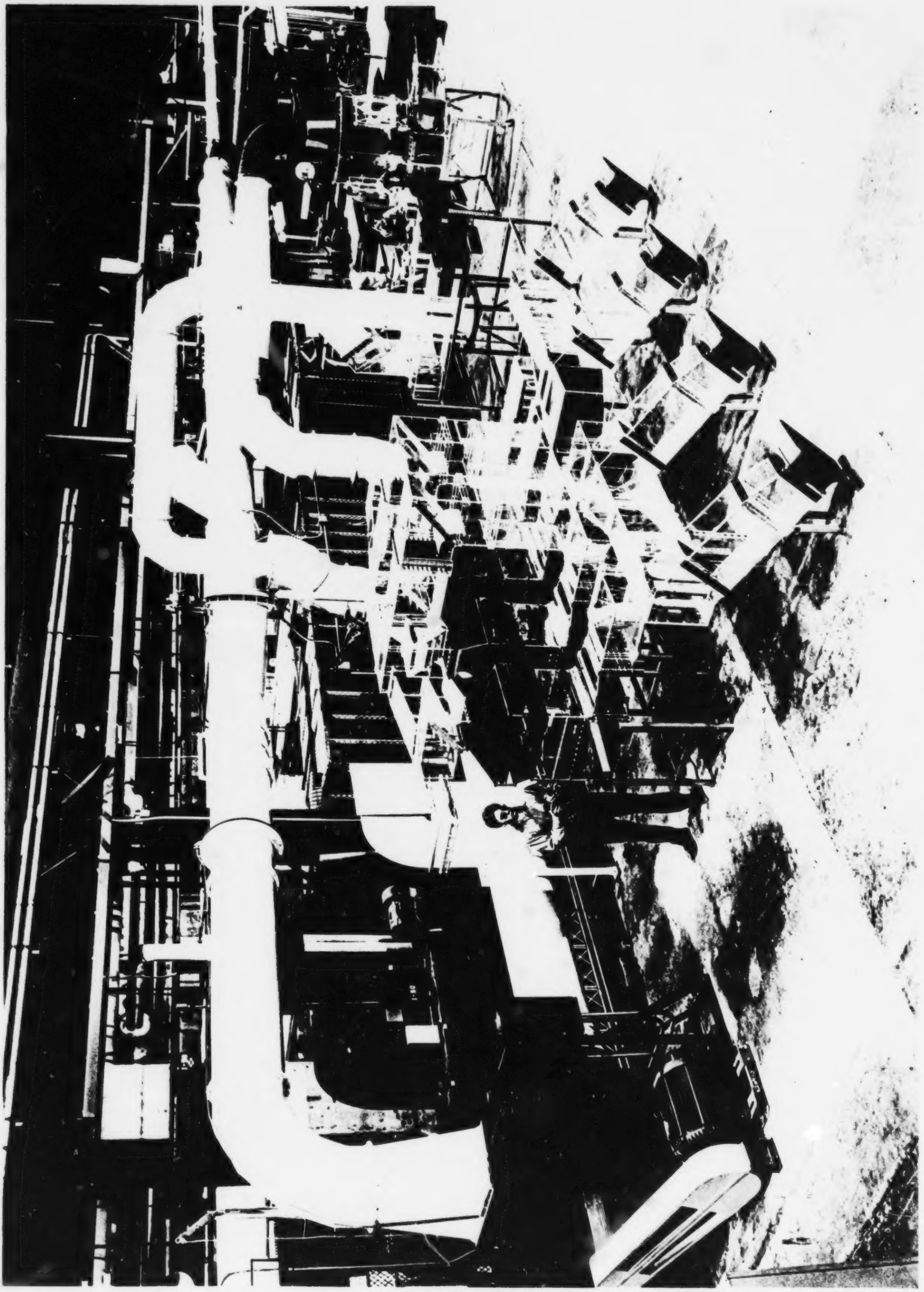


Figure 4-1. KDL/MSE Flow Model Test Facility

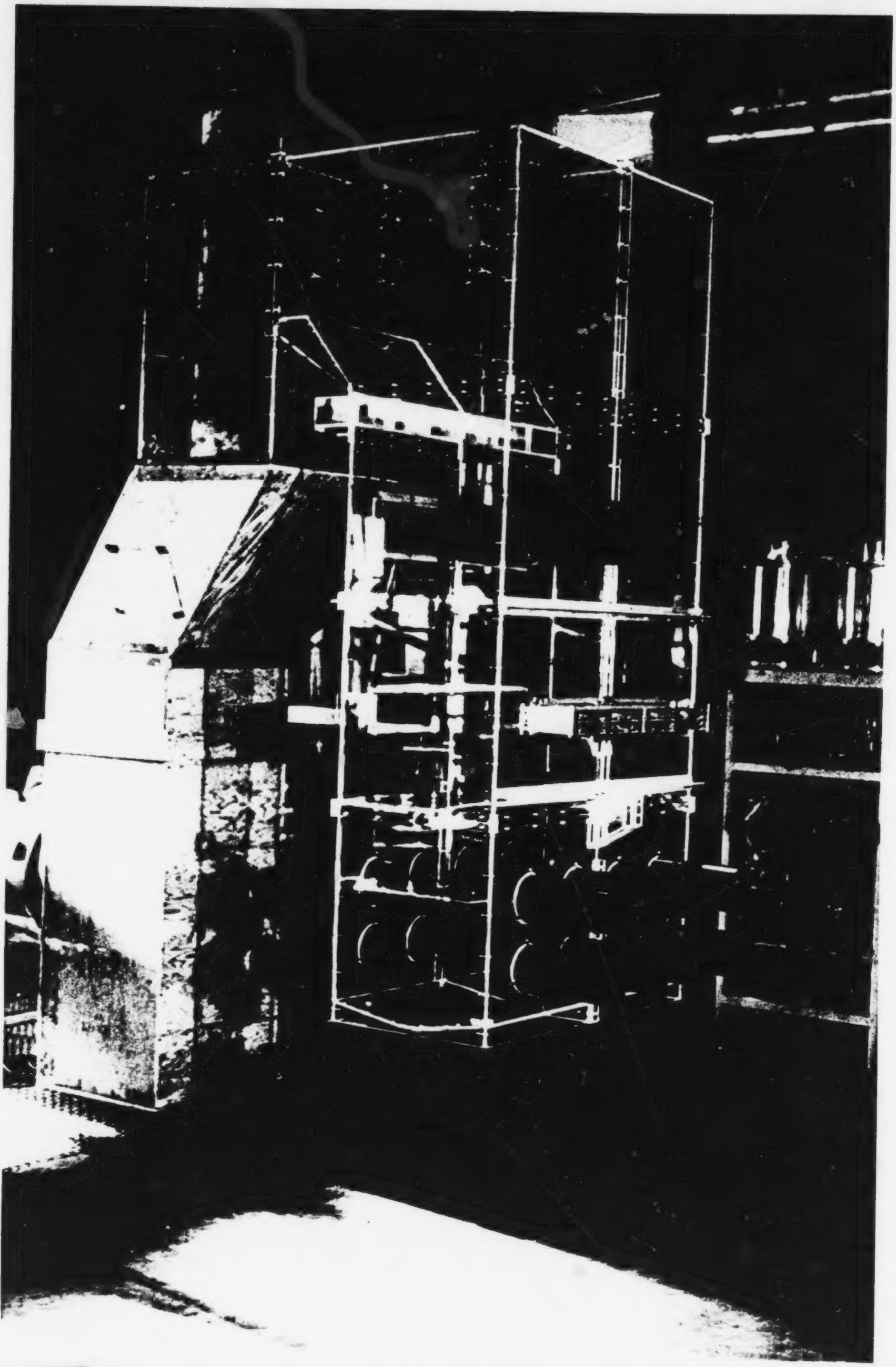


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Figure 4-2. Ladyzhinskaya Boiler Model

in the prototype Laydzhinskaya boiler. Figure 4-3 details the completed heat transfer section as installed in the flow model.

The flow model was operated under suction (induced draft) using air at approximately standard temperature and pressure. Bell mouths were added to the inlets to the main burners to reduce the entrance losses and to provide uniform velocity profiles at the inlet to the model.

Particular attention was paid to the design of the main burners, Figure 4-4, the "dump" burner nozzles, Figure 4-5 and the gas recirculation nozzles, Figure 4-6. The nozzles exit areas ("free areas") of these components were adjusted according to criteria detailed in the subsequent modelling approach section of this report. Swirlers were added to the secondary air streams of the main burners, Figure 4-7. These swirlers were designed so as to maintain the same Swirl Number (ratio of axial to tangential momentum) between the model and the prototype.

Figure 4-8 shows one of the typical reburn fuel and burnout air nozzle injector banks used during this study. Figure 4-9 presents a cross-sectional slice view of this nozzle. The banks were fabricated from sheet steel with nozzle widths varying as required to simulate the various injection velocities. The nozzle bank fit into a slot arrangement on the flow model and provided for the easy adjustment of injection tilt during model operation. During the flow visualization tests, the nozzles were operated under suction (induced draft) to facilitate the introduction of jet tracing smoke.

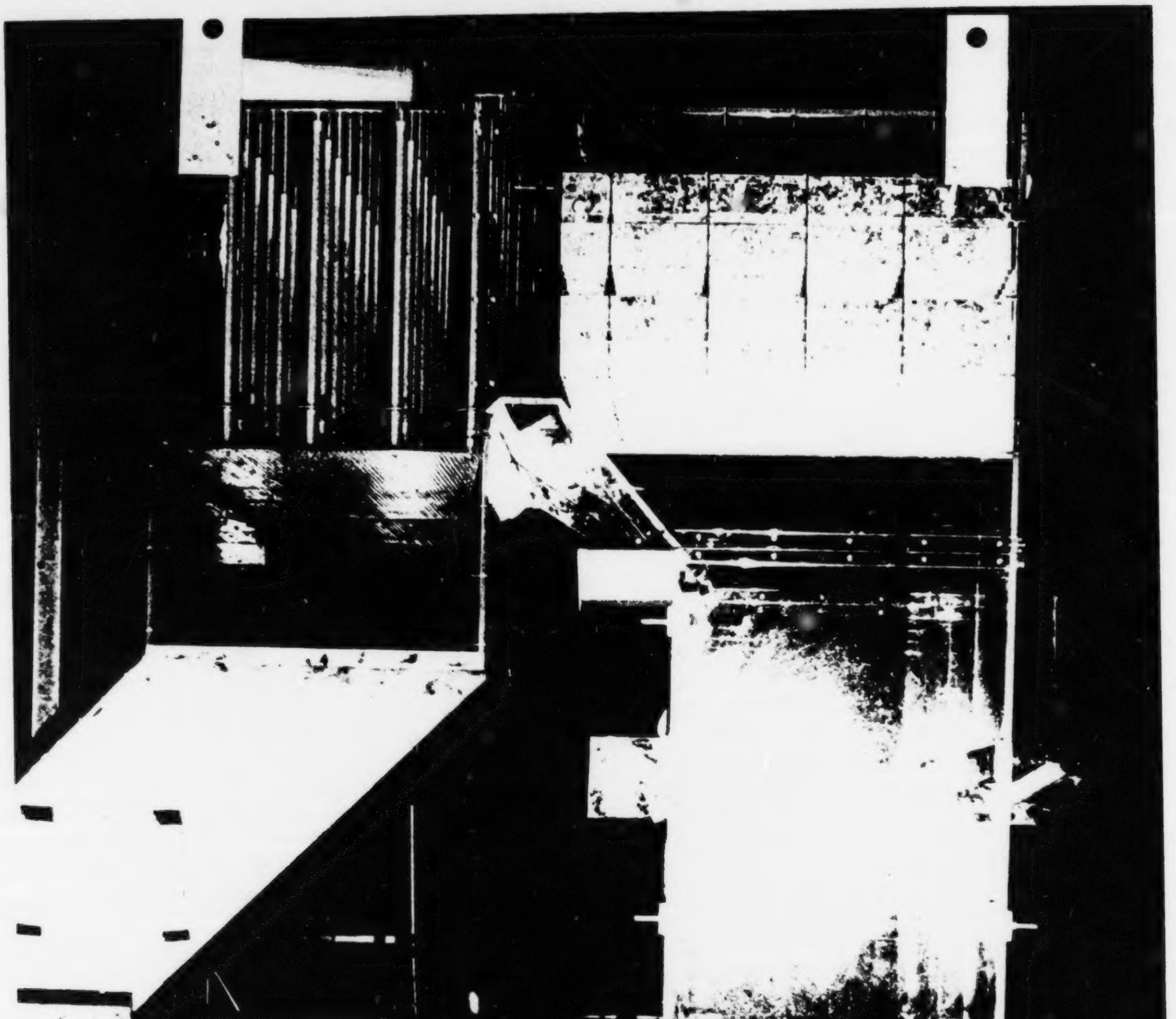

Figure 4-3. Heat Transfer Section - Boiler Model

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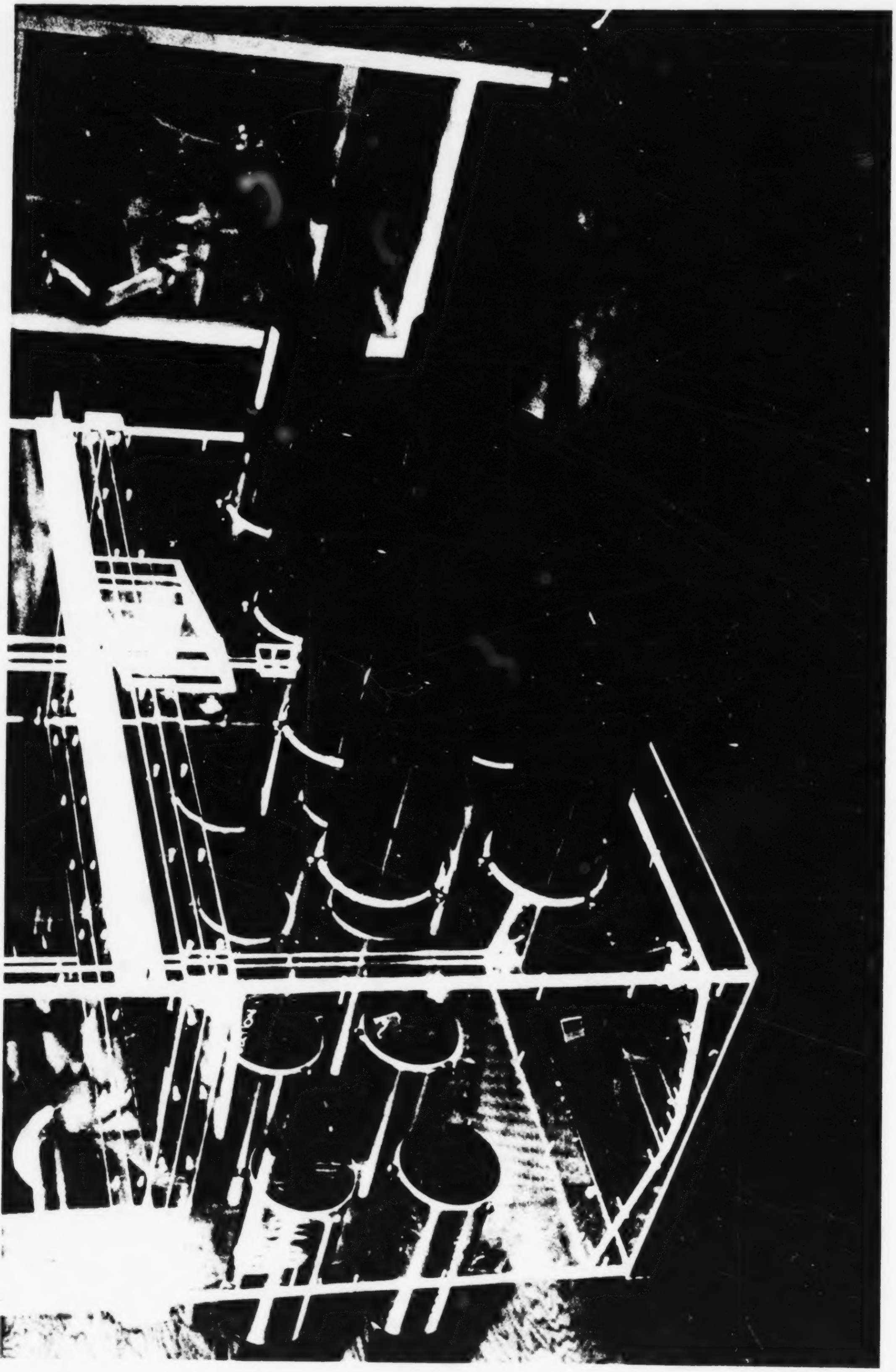

Figure 4-4. Main Burner Model Details

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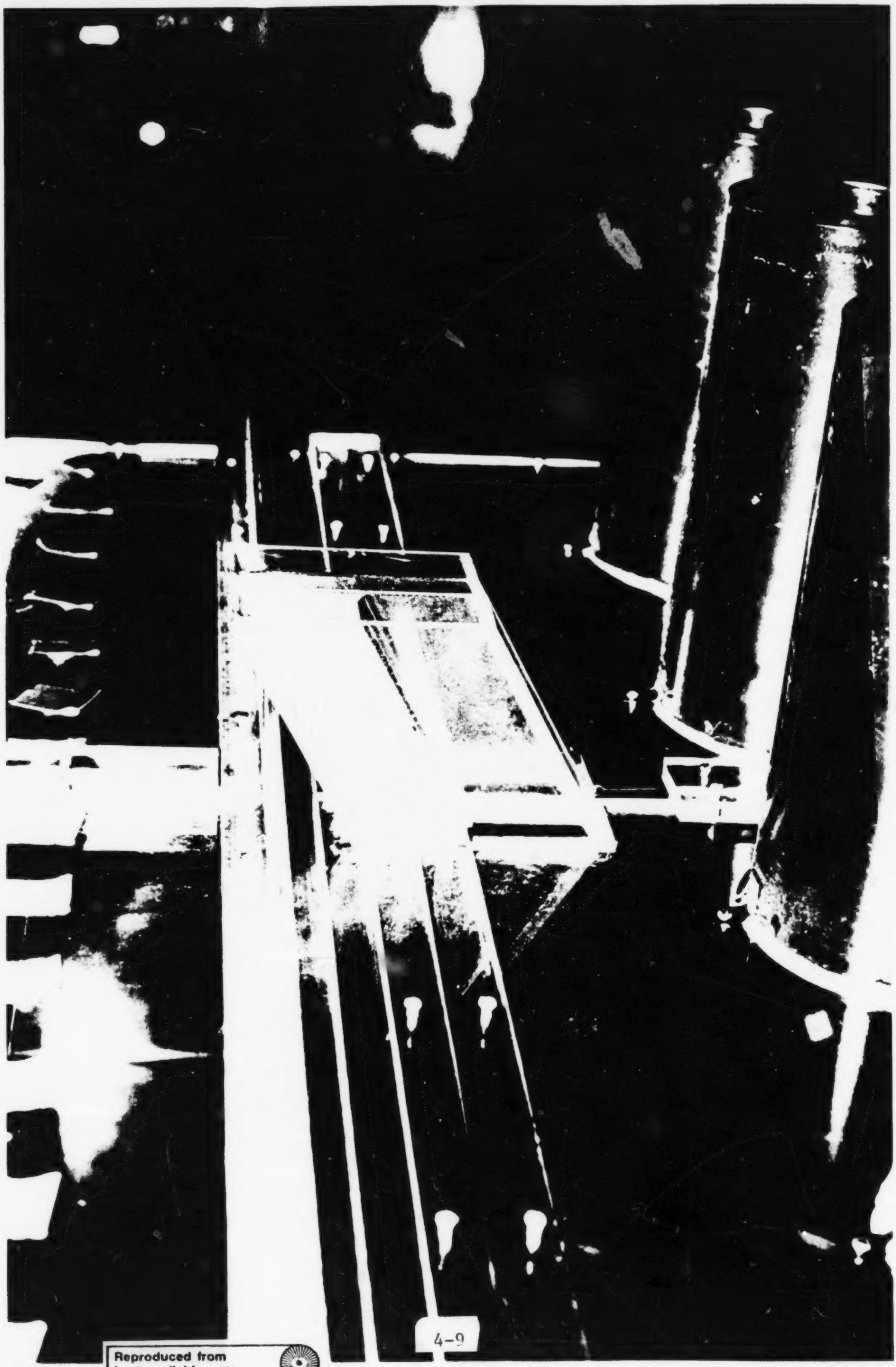

Figure 4-5. "Dump" Burner Model Details

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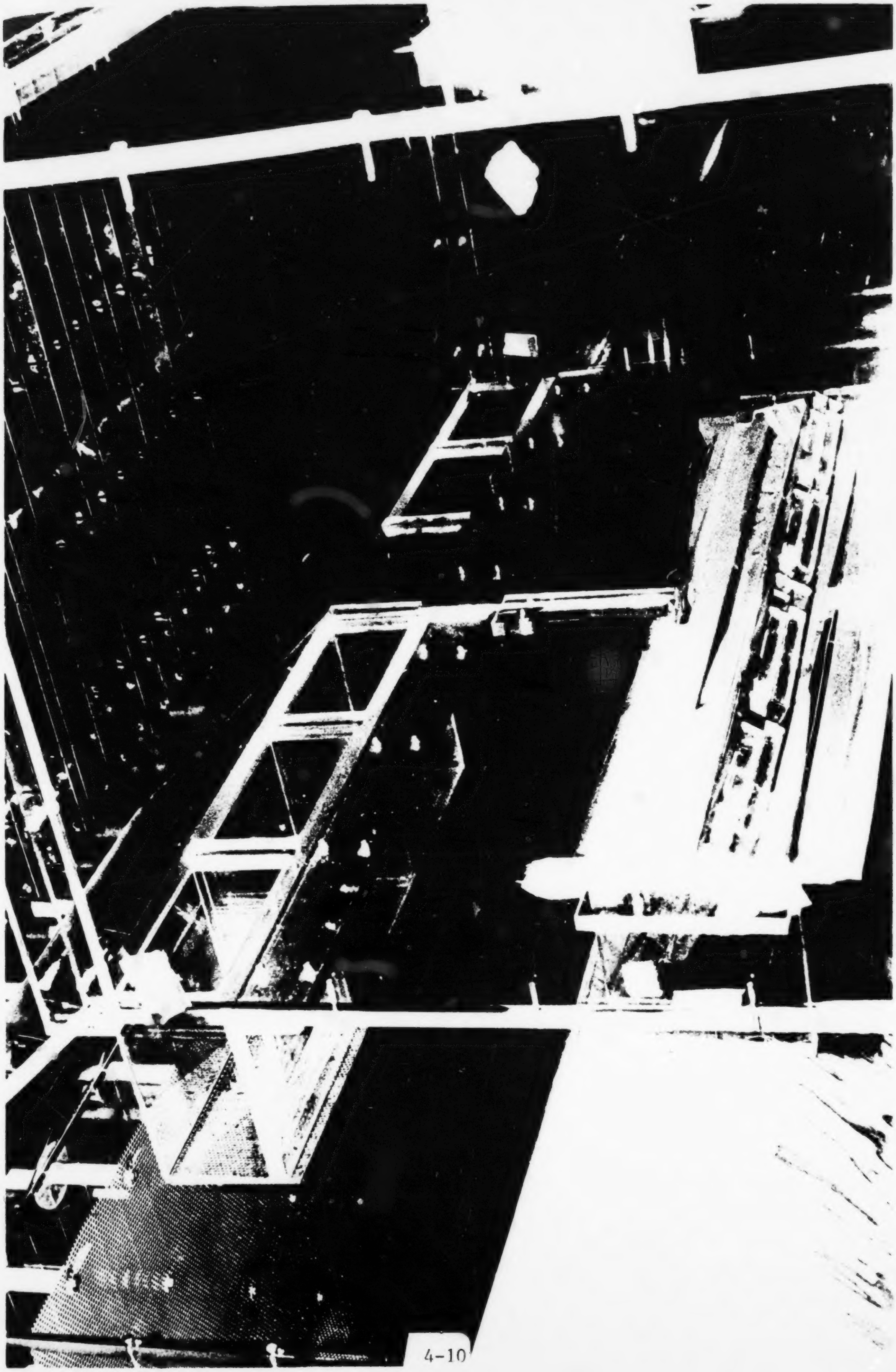


Figure 4-6. Gas Recirculation Nozzle Model Details

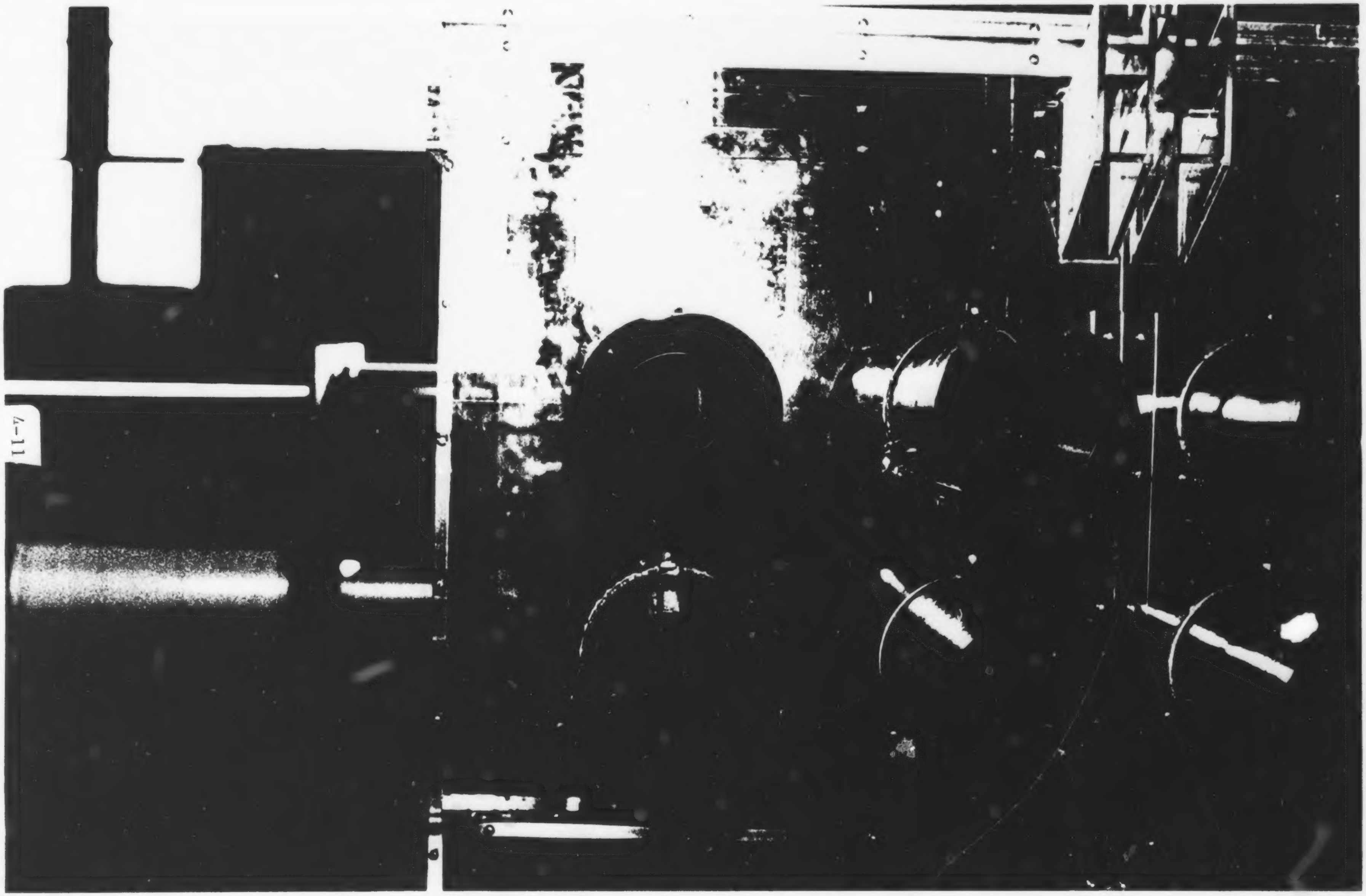


Figure 4-7. Burner Swirler Model Details

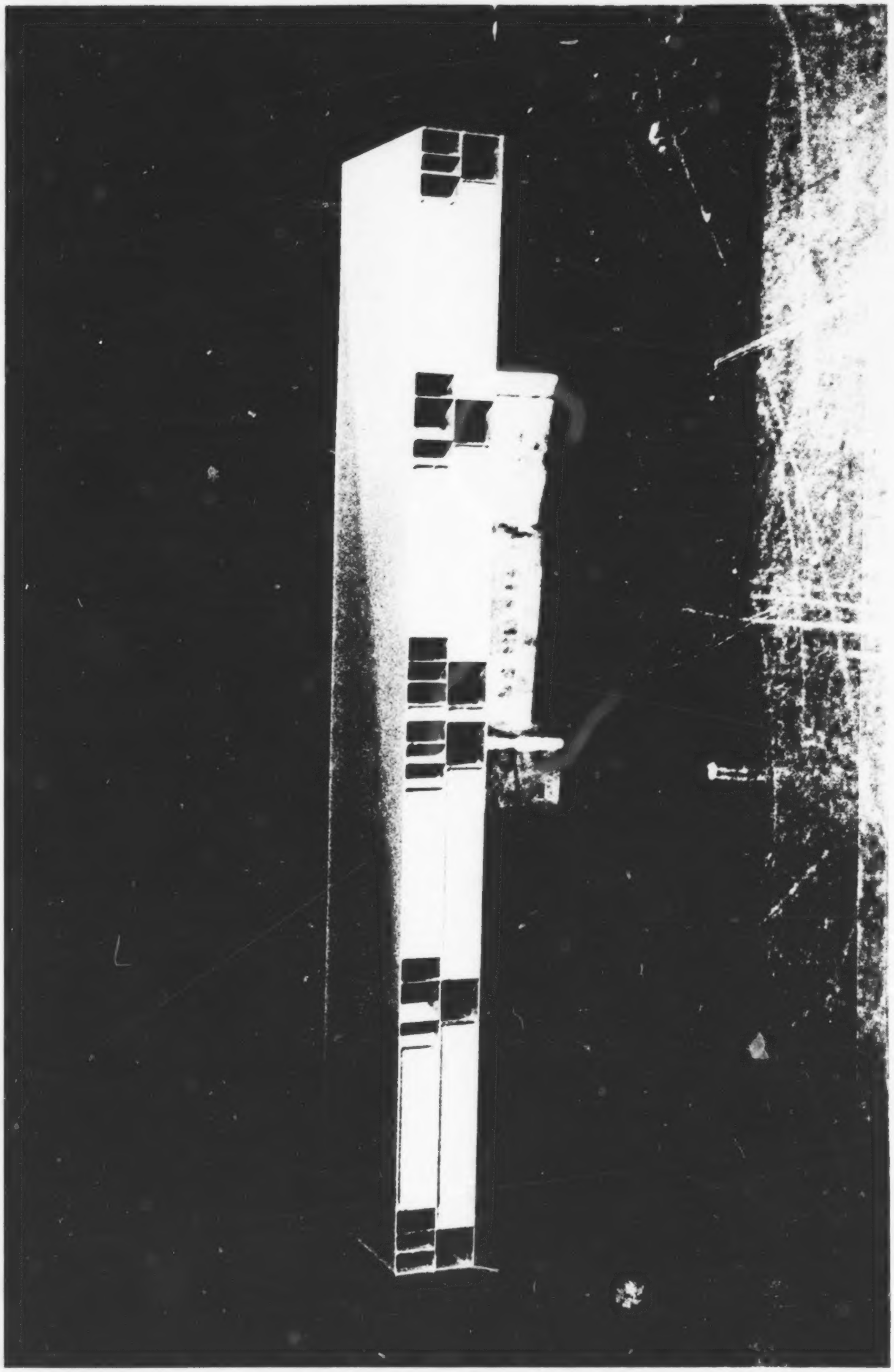
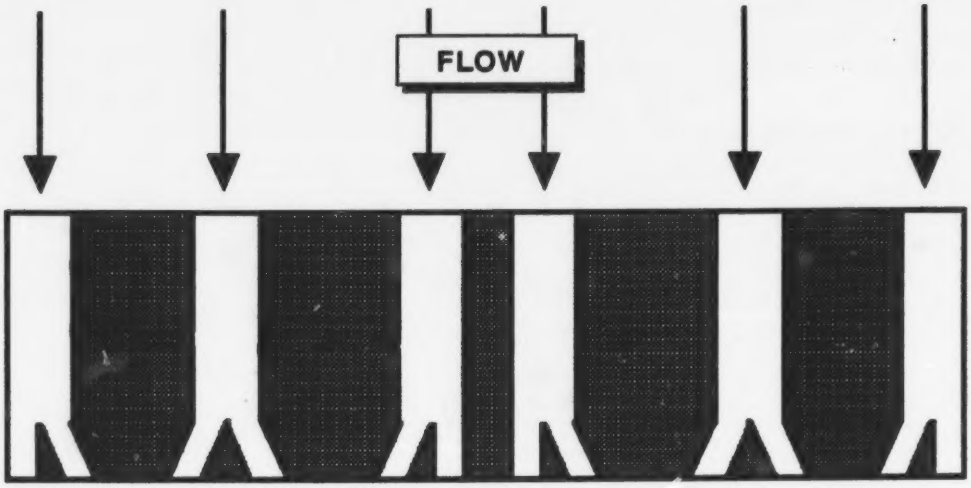
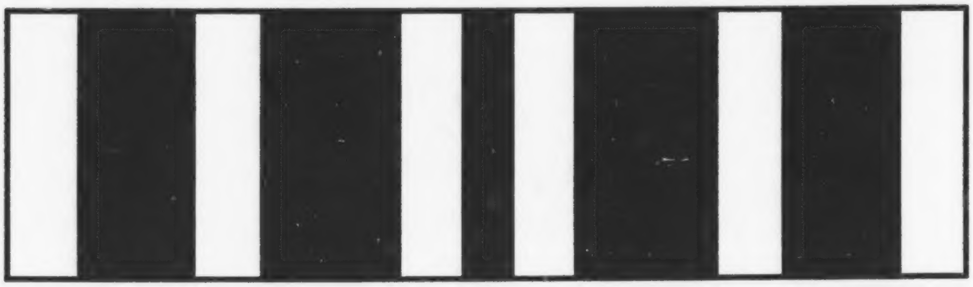


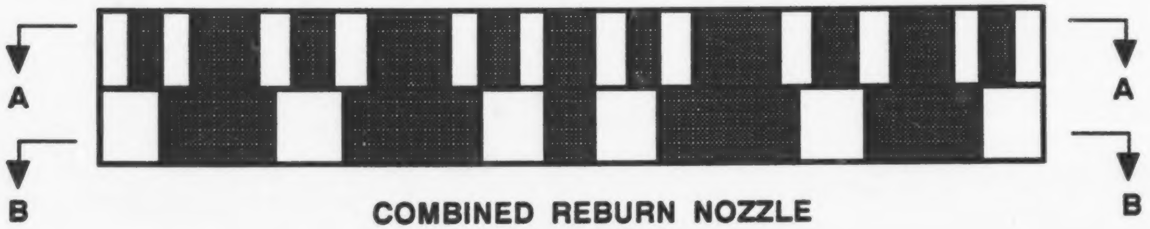
Figure 4-8. Model of Reburn Fuel/Burnout Air Injector Bank



TOP LEVEL OF NOZZLES
SECTION "AA"



BOTTOM LEVEL OF NOZZLES
SECTION "BB"



COMBINED REBURN NOZZLE
ASSEMBLY
FRONT ELEVATION

Figure 4-9. Schematics of Reburn Fuel/Burnout Air Injector Banks

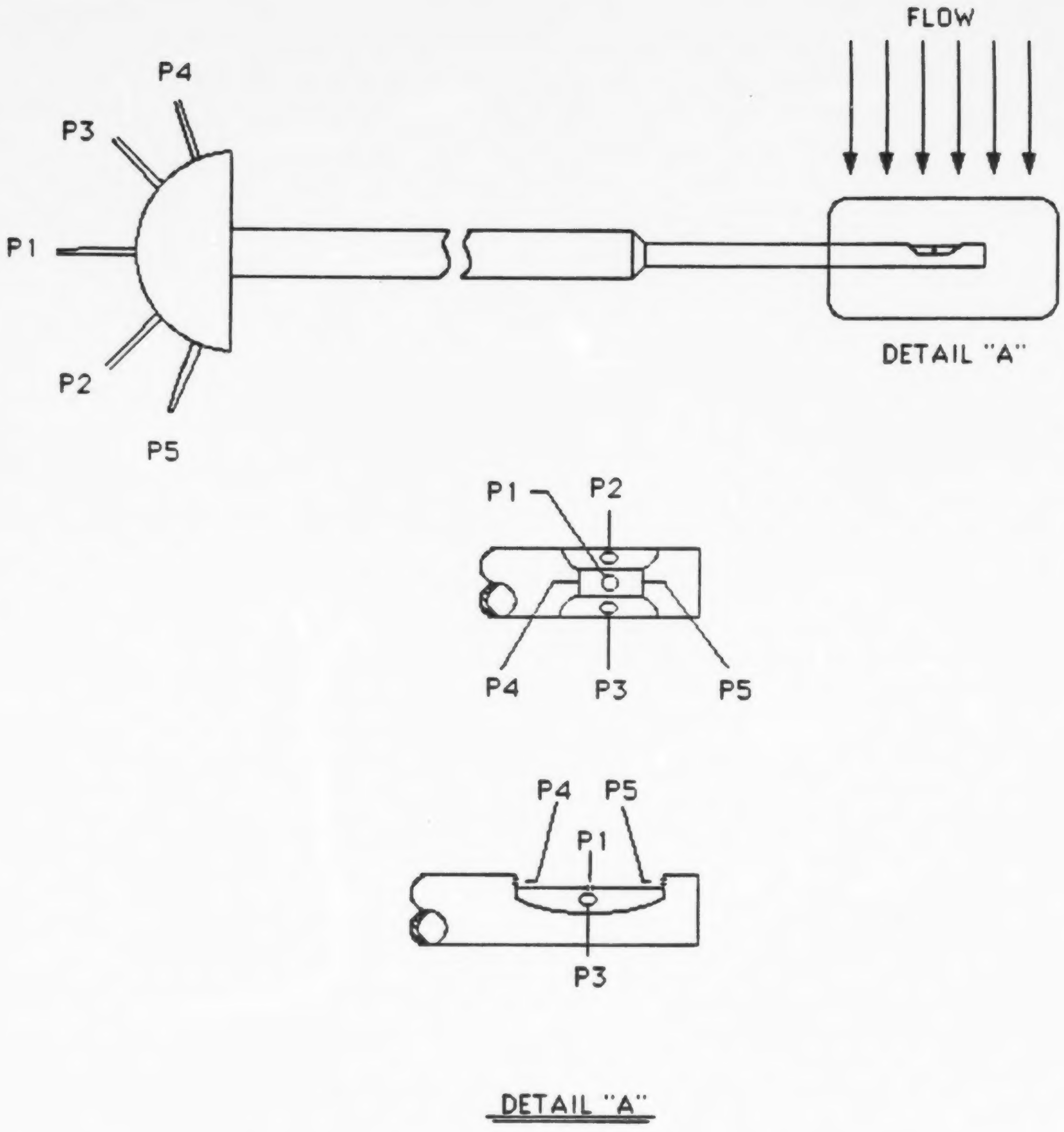
TEST INSTRUMENTATION

A number of instrumentation systems were used during the test program including an automatically controlled three dimensional pitot tube probe traversing system. Each instrumentation system was calibrated (National Bureau of Standards traceable) before and after each test series. These systems and the equipment used in the flow visualization experiments are briefly discussed below.

Three-Dimensional Pitot Tube Probe

A commercially available five-hole directional sensing pitot tube probe, shown schematically in Figure 4-10, was used. The probe has five pressure sensing holes located at its tip. The centrally located pressure hole, P1, measures the total or impact pressure of the fluid, while the two lateral holes, P2 and P3, measure the static pressure. If the probe is rotated around its long axis until P2=P3, the plane of the flow can be identified and measured. Since the condition P2=P3 will be found at two locations 180° apart, the correct flow vector plane is identified when P2=P3 and P1 has its highest positive value with respect to P2 and P3. An angular encoder is attached to the probe at its base so that the angle of this vector plane, commonly called the yaw angle, can be measured. The yaw angle indicates the plane of flow but does not give the flow angle within this plane. This flow angle, known as the pitch is determined by the differential pressure P4-P5.

In actual practice, four (4) differential pressure readings are required to fully define the flow at a particular point in the flow field of interest. These pressure differentials are:


FLOW
P4
P3
P1
P2
P5
DETAIL "A"
P1
P2
P4
P3
P5
P4
P5
P1
P3
DETAIL "A"

Five Hole Pitot Tube Probe

Figure 4-10. Five Hole Pitot Tube Probe

P1-Patm - Indicated total pressure with respect to atmosphere

P1-P2 - Indicated velocity pressure

P2-P3 - Yaw angle pressure

P4-P5 - Pitch angle pressure

Calibration curves are used to relate these pressure differentials to the actual pressures and pitch angles. These curves are generated through detailed probe calibrations at the beginning and end of each test series. These curves enable the experimenter to determine the actual velocity head and pitch angle of the flow at each measurement point. Knowing this data and the yaw angle, the x, y, and z or the normal, radial, and tangential velocity vectors are determined using simple geometric relationships.

Automatic Probe Traversing Device

All quantitative three-dimensional velocity and pressure mapping within the flow models were obtained with a calibrated five-hole pitot tube coupled to a computer controlled traversing device and data acquisition system. This system, which was developed and built at KDL, is called the Automatic Probe Traversing Device or APTD.

The APTD (Figure 4-11) is a programmable data acquisition system which automatically positions and then records all pressure readings on the laboratories central computer system. Figure 4-11 shows the five-hole pitot tube, the APTD, and local programmable controller/electronic manometer cabinet. The motion of the probe is controlled by the system's local processor. This process is programmed by the facilities operator at the

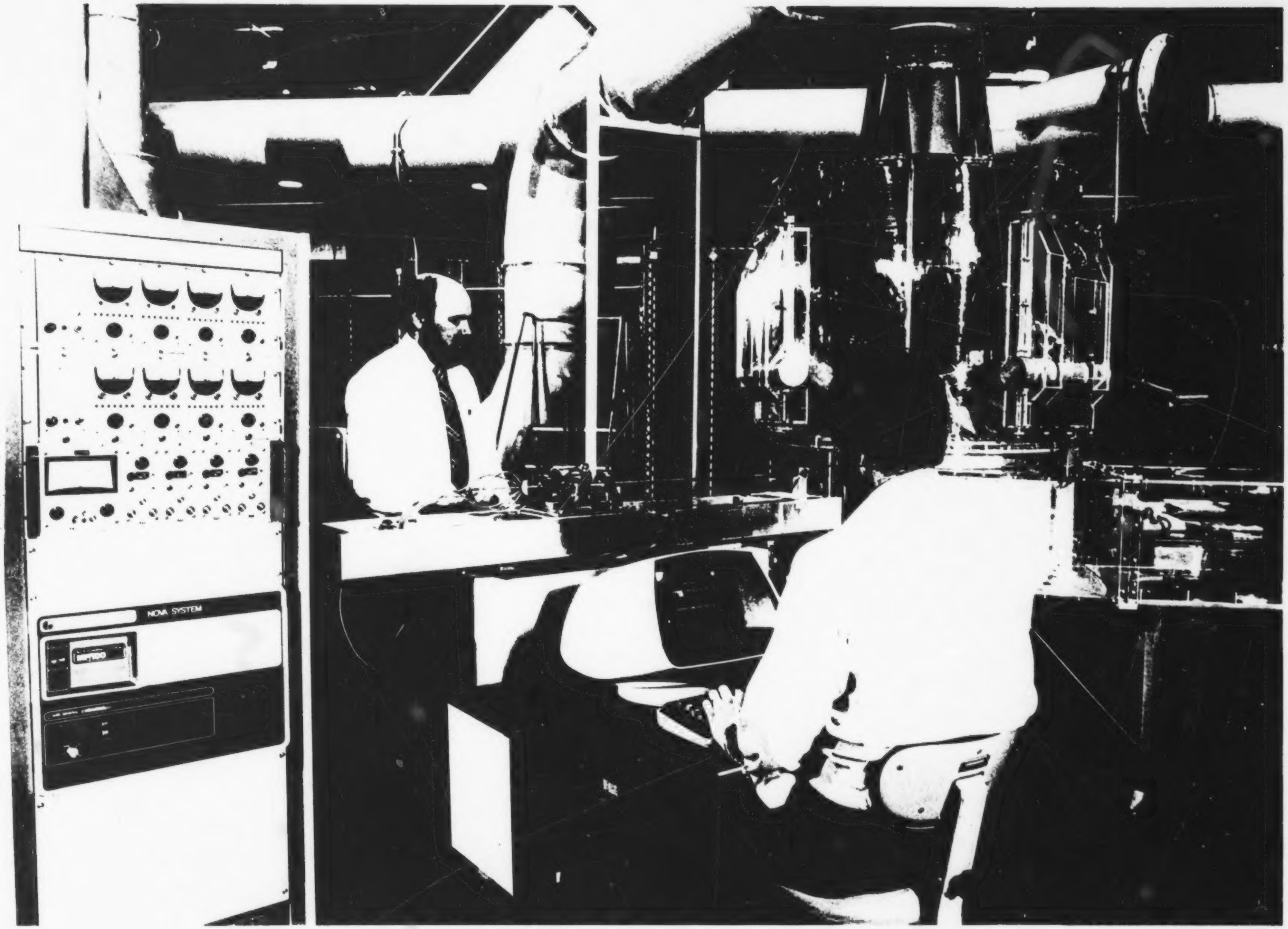

NOVA SYSTEM

Figure 4-11. Automatic Probe Traversing Device

start of each instrumentation traverse by entering the appropriate operational parameters of the particular test. These parameters include: instrument type and serial number (for accessing the most recent calibrations), test number, test plane, the number of data points to be obtained, the distance between each test point, and the maximum distance of probe travel (a safety feature). Once these operational parameters have been entered, the traverse can be started by indicating the desired automatic operational mode.

The processor controls stepping motors which move the probe to the preprogrammed test point location and rotates it until the direction of flow is obtained. The outputs of the four pressure transmitters, measuring the differentials listed above, are then recorded along with the probe position, angle, test number, test plane, etc. by the central data acquisition computer.

Smoke Generator

A commercially available smoke generator was utilized during the flow visualization tests. The smoke generation system consisted of a gas heater, light oil smoke fluid reservoir, and tube coil. Gas heating of the tube coil through which the fluid was pumped was used to flash the fluid into a dense white stream of smoke which was then injected into the flow model. Figure 4-12 shows the smoke generator being used during a typical flow visualization test.

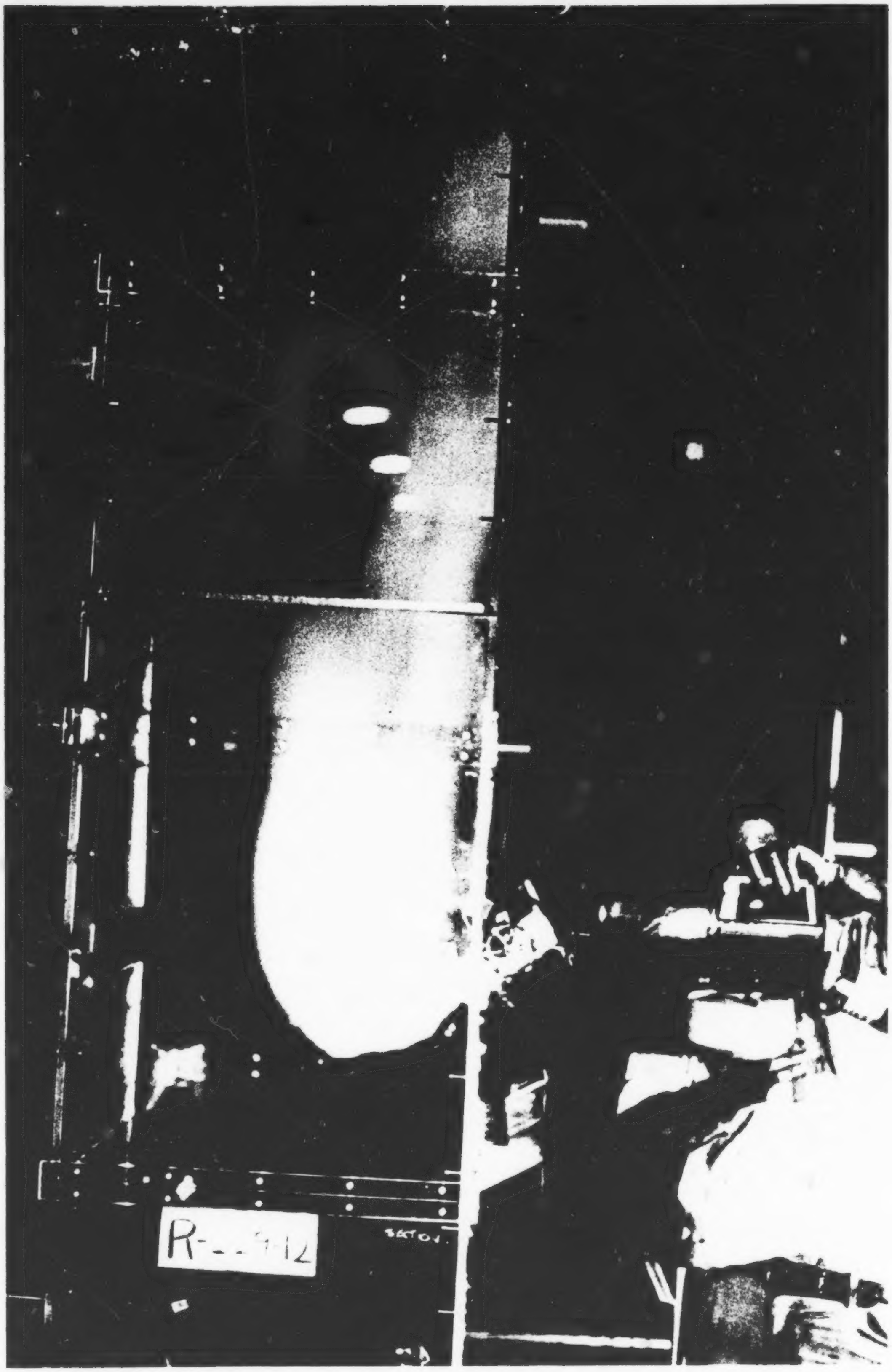


Figure 4-12. Smoke Generator

Color Video System

The flow visualization tests results were documented using a commercially available closed circuit color video tape system. The variable speed, stop action, and color reversal capabilities of the system during playback proved to be very useful tools. Also, the ability to evaluate the test results for the various designs, which were taken over a period of several days, together in one session improved interpretation of the design configurations.

MODELING APPROACH

The use of isothermal flow models in predicting the performance of furnace systems has long been recognized as a powerful tool. This is because conditions inside existing or proposed equipment, hereafter called the prototype, can be simulated by experiments in models which are smaller in size than the prototype, and operate at lower temperatures. Such models yield qualitative information (visual flow observations) as well as quantitative information in the form of but not limited to velocity profiles, pressure distributions, and gas mixing data. These are important for the evaluation of unit operation and/or performance.

In the Ladyzhinskaya furnace, fuel and air are introduced into the furnace from sixteen swirl burners divided between the front and rear walls of the unit. The swirl from these burners, and the combining primary fuel and air streams create the necessary turbulence for mixing and combustion. The furnace thus serves as both a mixing and combustion chamber and a burner for combustion. Additionally, flue gas is recirculated to the rear wall of the furnace near the arch of the unit in order to control convective section steam and metal temperatures.

For an accurate simulation of the fluid mechanics in an operating furnace, a physical model must duplicate the controlling fluid mechanic phenomena. These include: mixing of the hot and cold flow streams, mixing of the crossflow jets into the main swirling flow and the interaction of these jets in the combustion zone.

As detailed by Beer and Chigier (10), it is possible to model combustion systems via the use of geometric, mechanical (kinematic or dynamic), and thermal similarity parameters. However, Beer (11) and Spaulding (12) both point out that it is not possible to reproduce all the prototype's processes in a model and it is an important engineering task to critically select the most important parameters. This task, the so-called "art of partial modeling", is based on modeling only the dominant processes and relating the conditions for similarity to physical observations. This modeling technique has been successfully verified in a number of studies, most recently by Anderson and Bianca (13), where the results of flow model studies have been correlated to field observations and measurements.

As previously noted, this model study investigated the mixing and dispersion performance of potential reburn fuel and burnout air jets with the bulk furnace gasses. In light of this, particular interest was paid to those similarity groups involved with these physical processes.

For combustion systems Chigier (14), in agreement with the accepted modeling practice of Johnstone and Thring (15), has noted that certain similarity criteria are more important than others. Therefore, based on the previously discussed references and KDL's extensive past modeling experience (16) on full scale coal fired furnaces the following general modeling guidelines were used:

1. Geometric Similarity

As far as possible, the isothermal flow model must be constructed geometrically similar to the prototype. This can be achieved by using a scale factor between all dimensions in the model and the prototype. As in any physical model, the linear scale factor, S, is defined as;

$$S = \frac{\text{representative length in the prototype}}{\text{representative length in the model}}$$

For the Ladyzhinskaya furnace model, a value of S = 16 (1/16 scale) was selected on the basis of available fan capacity, velocity measurement limitations and confidence in the test results obtained. Geometric similarity of the main coal burners and reburn and burnout air nozzles was abandoned; these components were scaled according to dynamic similarity criteria to be discussed in a following section.

2. Reynolds Number

The literature has shown that if the Reynolds number exceeds 10,000, the transfer processes of momentum, heat and mass transfer are controlled by the turbulent forces and molecular transport processes can be neglected. Thus, as long as the Reynolds number (based on the overall furnace conditions) is greater than 10,000 one does not have to equate Reynolds number between the model and prototype.

3. Non-Isothermal Conditions

It is standard modeling practice to oversize the burners in isothermal furnace flow models to account for the rapid expansion of gasses exiting the burners due to the combustion of the fuel and air and the corresponding reduction in momentum flux at the flame front. This expansion is sized according to the Thring-Newby criteria (17), and has been used in Combustion Engineering model studies for over 30 years. For this study, the exit cross-sectional area of the burners was increased by a factor of approximately three, which was equivalent to the ratio of the prototype's burner inlet gas density to combustion zone gas densities.

4. Jet Modeling

Similitude in jet penetration and dispersion were obtained when the jet to crossflow mass ratio between the model and the prototype were equal while approximating the non-dimensional jet trajectories between them. That is;

$$\text{Normalized Jet Trajectory (model)} = \text{Normalized Jet Trajectory (prototype)}$$

$$\left(\frac{M_{jet}}{M_{crossflow}}\right)_{model} = \left(\frac{M_{jet}}{M_{crossflow}}\right)_{prototype}$$

Simplifying assumptions based on modeling criteria developed by examining single jet trajectories in a crossflow, illustrated by Figure 4-13, have been used in designing the jet components of three-dimensional airflow models. Jet penetration characteristics (18, 10) have been studied in KDL in order to determine the appropriate criteria which will provide the desired model to prototype jet similitude.

By satisfying the criteria detailed in these references, similitude between the model and the prototype non-dimensional jet trajectories was insured as long as the jet-to-cross flow mass ratios for the model and the prototype were identical and the prototype gas densities of the crossflow and jet do not change. In the isothermal Ladyzhinskaya flow model, the main burner, reburn fuel, burnout air, gas recirculation and dump burner nozzle sizes were adjusted according to this criteria.

IDENTIFICATION OF CANDIDATE REBURN SYSTEM CONFIGURATIONS

Selection of candidate reburn fuel and burnout air injection configurations for the Ladyzhinskaya furnace flow model required two types of initial specification; injection location and injection velocity. The specifications are discussed below.

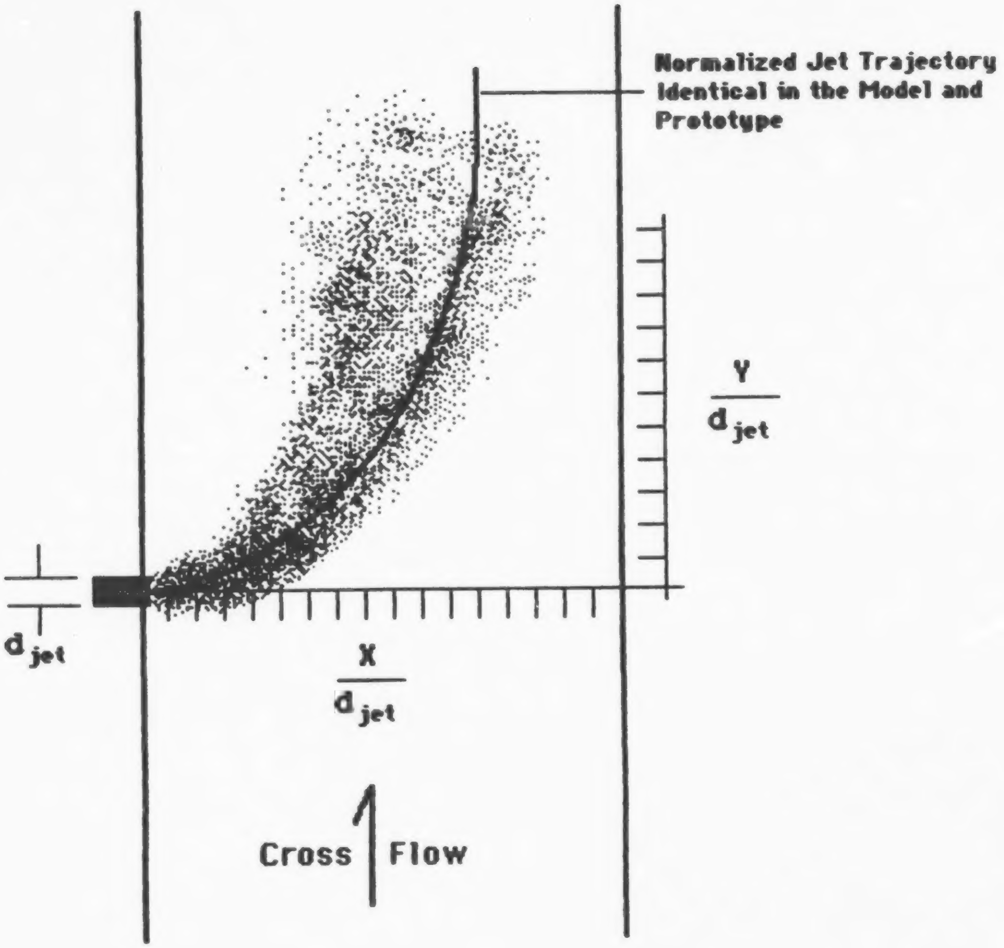

Normalized Jet Trajectory Identical in the Model and Prototype
Y / d jet
X / d jet
d jet
Cross Flow

Figure 4-13. Jet in Cross Flow

Identification of Reburn System Nozzle Design and Injection Velocity

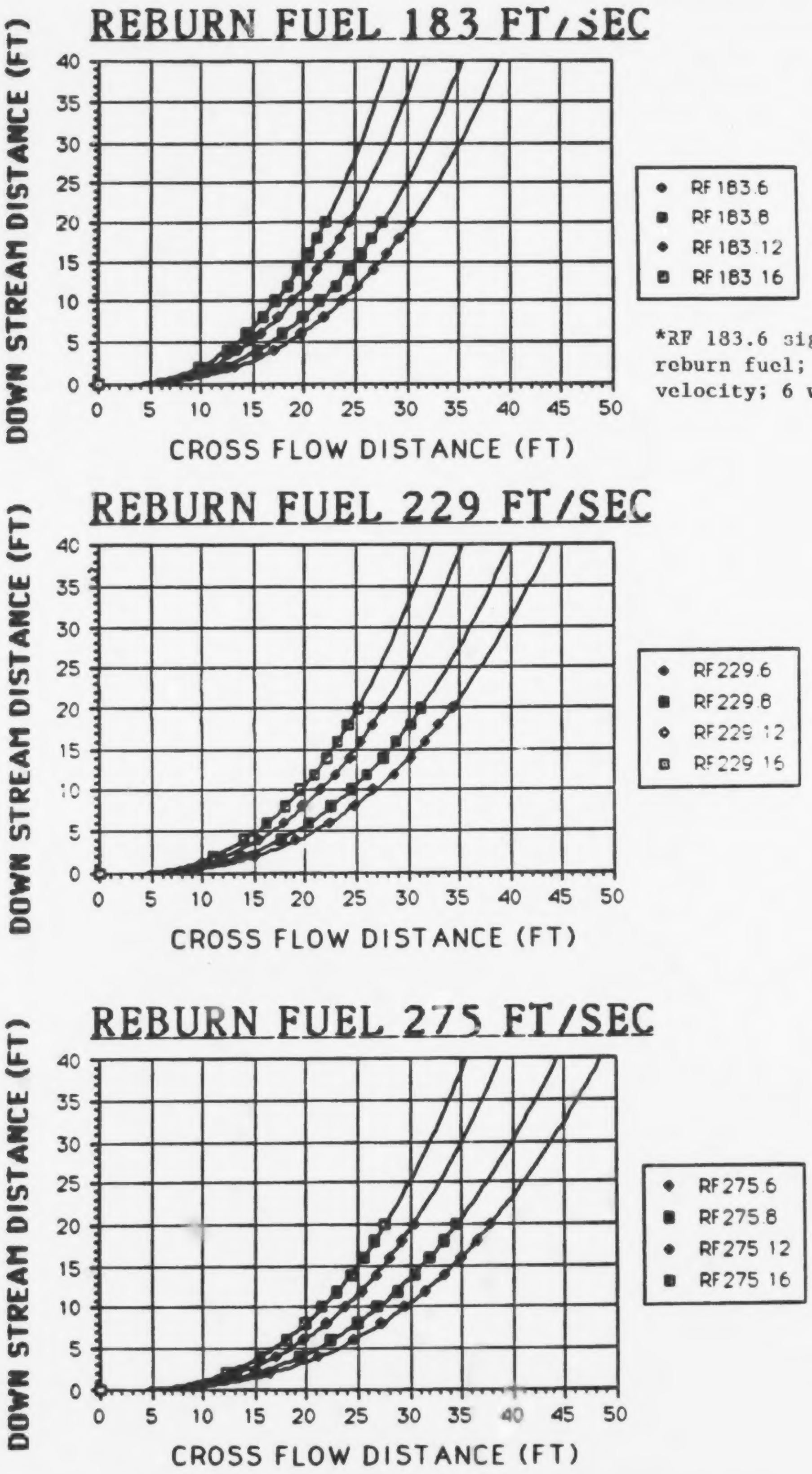
Based on the results of the previously discussed reburn system process flow/mass balance calculations, the required mass flow rates of the reburn fuel, carrier gas recirculation and burnout air were specified.

From this information and using the jet modeling criteria discussed previously, a series of jet trajectory calculations were performed to evaluate the penetration performance of both the reburn fuel and burnout air injection systems over a range of injection velocities, 183, 229, and 275 ft/sec (56, 70 and 84 m/sec) and configurations consisting of 6, 8, 12 and 16 injection nozzles. The results of these calculations are shown in Figures 4-14 and 4-15. From these calculations, it was determined that an injection velocity of 275 ft/sec (84 m/sec) was excessive as there was a definite possibility of jet impact on the opposite wall. It was therefore decided that the velocity range to be evaluated should be lowered. A new minimum velocity of 146 ft/sec (45 m/sec) was chosen. Table 4-1 presents the test matrices for both the reburn fuel and burnout air injection system evaluations.

Based on past experience with furnace injection nozzle design, the injection nozzles for both the reburn fuel and burnout air were designed with 0 to -30° vertical tilt capability.

Figure 4-16 presents the design of both the reburn fuel and burnout air injection windboxes. On the prototype unit each windbox injection location will consist of two or three nozzles for the reburn and burnout air

1 FOOT (FT) = .3048 METERS (M)



*RF 183.6 signifies reburn fuel; 183ft/sec jet velocity; 6 windbox locatio

Figure 4-14. Jet Trajectory Calculations For Reburn Fuel Jets

1 FOOT (FT) = .3048 METERS (M)

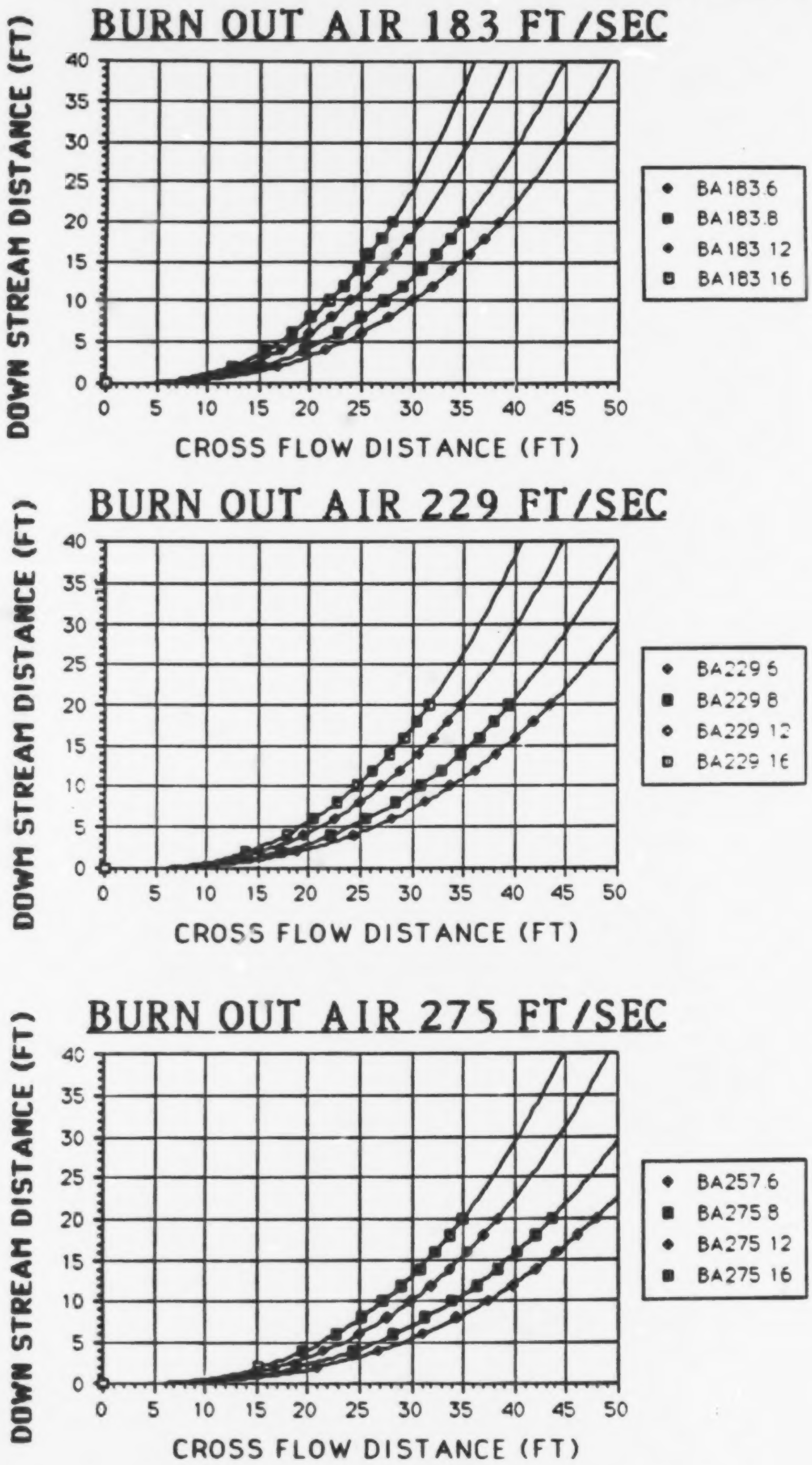


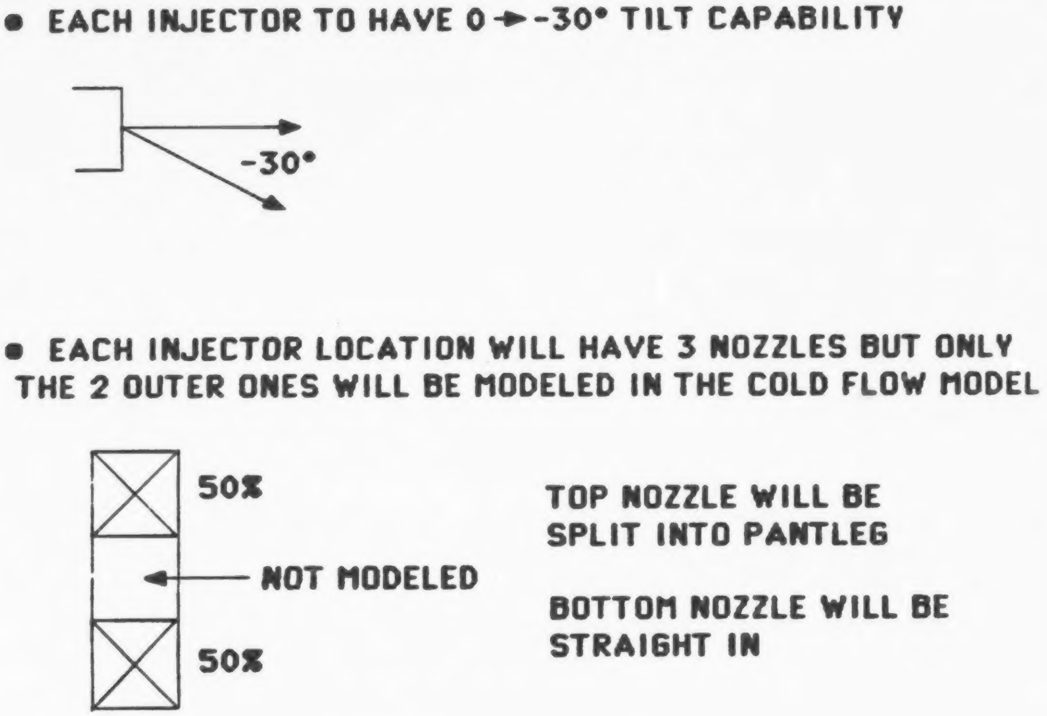
Figure 4-15. Jet Trajectory Calculations For Burnout Air Jets

Table 4-1. Physical Flow Modeling Test Matrix

- **TEST MATRIX (IDENTICAL FOR BOTH REBURN FUEL & BURNOUT AIR)**

TEST #	DESCRIPTION	TILT	VELOCITY (FT/SEC)
1	6 FRONT 6 REAR	0 -30	146
2	6 FRONT 6 REAR	0 -30	183
3	6 FRONT 6 REAR	0 -30	229
4	6 FRONT -----	0 -30	146
5	6 FRONT -----	0 -30	183
6	6 FRONT -----	0 -30	229
7	----- 6 REAR	0 -30	146
8	----- 6 REAR	0 -30	183
9	----- 6 REAR	0 -30	229

1 FOOT (FT) = .3048 METERS (M)



- EACH INJECTOR TO HAVE 0 → -30° TILT CAPABILITY
- EACH INJECTOR LOCATION WILL HAVE 3 NOZZLES BUT ONLY THE 2 OUTER ONES WILL BE MODELED IN THE COLD FLOW MODEL

TOP NOZZLE WILL BE SPLIT INTO PANTLEG

BOTTOM NOZZLE WILL BE STRAIGHT IN

Figure 4-16. Reburn System Injector (Windbox) Detail

arrangements, respectively. The upper nozzles will be split into either an 18° or 35° pantleg arrangement. The split angle used was based on the windbox location. The split angle for the pantleg configuration was based on previous work. Figure 4-17 details the pantleg arrangements that were used on the flow model during the course of the test program. The bottom nozzle was a standard straight through natural gas nozzle. The middle nozzle which is planned for future oil/coal introduction was not modeled in the flow model. This was fortuitous in that by not modeling the middle nozzle the upper and lower, which were enlarged by the previously discussed modeling criteria, could be brought next to each other bringing their centerlines closer to their correct scale separation. If the middle nozzle was modeled, the increase in the diameter of the three nozzles required to meet the aforementioned jet modeling criteria, would force the centerlines of the nozzles to be spread apart.

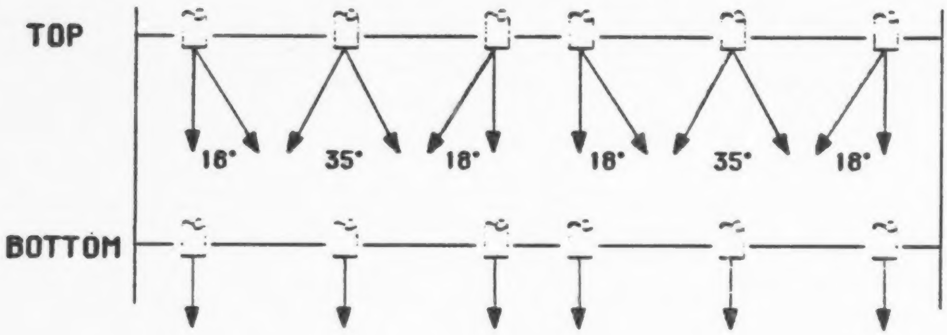
The choice of the horizontal spacing of the injection nozzles across the width of the furnace was chosen based on the waterwall tube circuits and was basically fixed to minimize retrofit complexity. Figure 4-18 details these spacings which were identical for both the front and rear mounted nozzles as well as for both the reburn fuel and burnout air systems.

Reburn System Flow Model Tests

BASELINE FLOW FIELD CHARACTERIZATIONS

The first series of tests to be performed in the cold flow model was a baseline evaluation of the furnaces aerodynamics with no reburn or burnout

- **NOZZLE SET UP:**

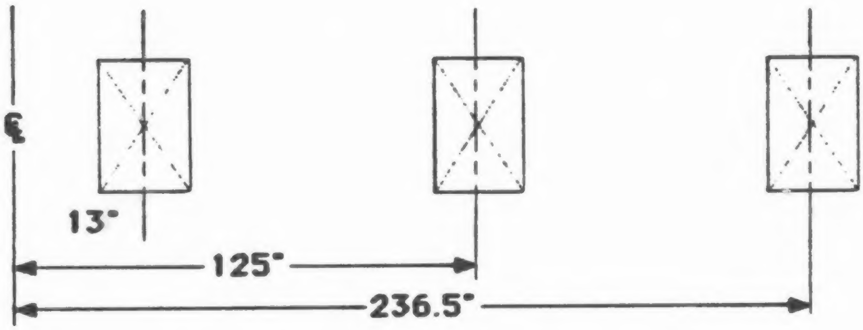

TOP
18°
35°
18°
18°
35°
18°
BOTTOM

- **3 VELOCITIES WILL BE MODELED: 146; 183; & 229 FT/SEC**

1 FOOT (FT) = .3048 METERS (M)

Figure 4-17. Pant-leg Arrangement For Upper Nozzles and Straight-Through Arrangement For Lower Nozzles in Each Windbox

- REBURN FUEL ELEVATION 20.3 m
- BURNOUT AIR ELEVATION 29.2 m
- 6 INJECTORS PER ELEVATION, SYMETRIC AROUND ℄



1 INCH (") = 2.54 CENTIMETER (CM)

Figure 4-18. Reburn System Injector Windbox Spacings

air injectors in operation. This evaluation included both flow visualization and limited quantitative three-dimensional velocity profiling.

Figure 4-19 shows observations made during the flow visualization tests, detailing the flow field in the area of the main burners. Note the effect of the high swirl secondary air of the main burners. This air spread out quickly and filled the combustion zone. The air from the simulated primary fuel-air nozzles was not swirled and therefore penetrated deeply into the center of the furnace where it impacted with the burner jets from the opposite wall. Some of this material was recirculated into the hopper indicating that some of the fuel, mostly from the lower elevation of burners, has a long residence time within the combustion zone of the furnace.

Figure 4-20 details the flow field observed when the flue gas recirculation (FGR) nozzle located near the arch of the furnace were identified with smoke. During these baseline flow visualization tests the total flue gas recirculation rate was set to 18%. It can be seen in this figure that the jets from these nozzles penetrated only 8-10% of the way across the unit. The gasses exited quickly and remained near the floor of the upper furnace.

Figure 4-21 details the flow fields observed when the unit's dump burners were identified with smoke. It can be seen that even though the burners were angled 30° downward or against the bulk furnace gas flow, little down-stream penetration was observed. An occasional wisp of smoke was seen to be recirculated into the lower furnace combustion zone. Because of the low elevation of these burners with respect to the rest of the unit, the gasses from these burners had plenty of time to disperse within the furnace volume.

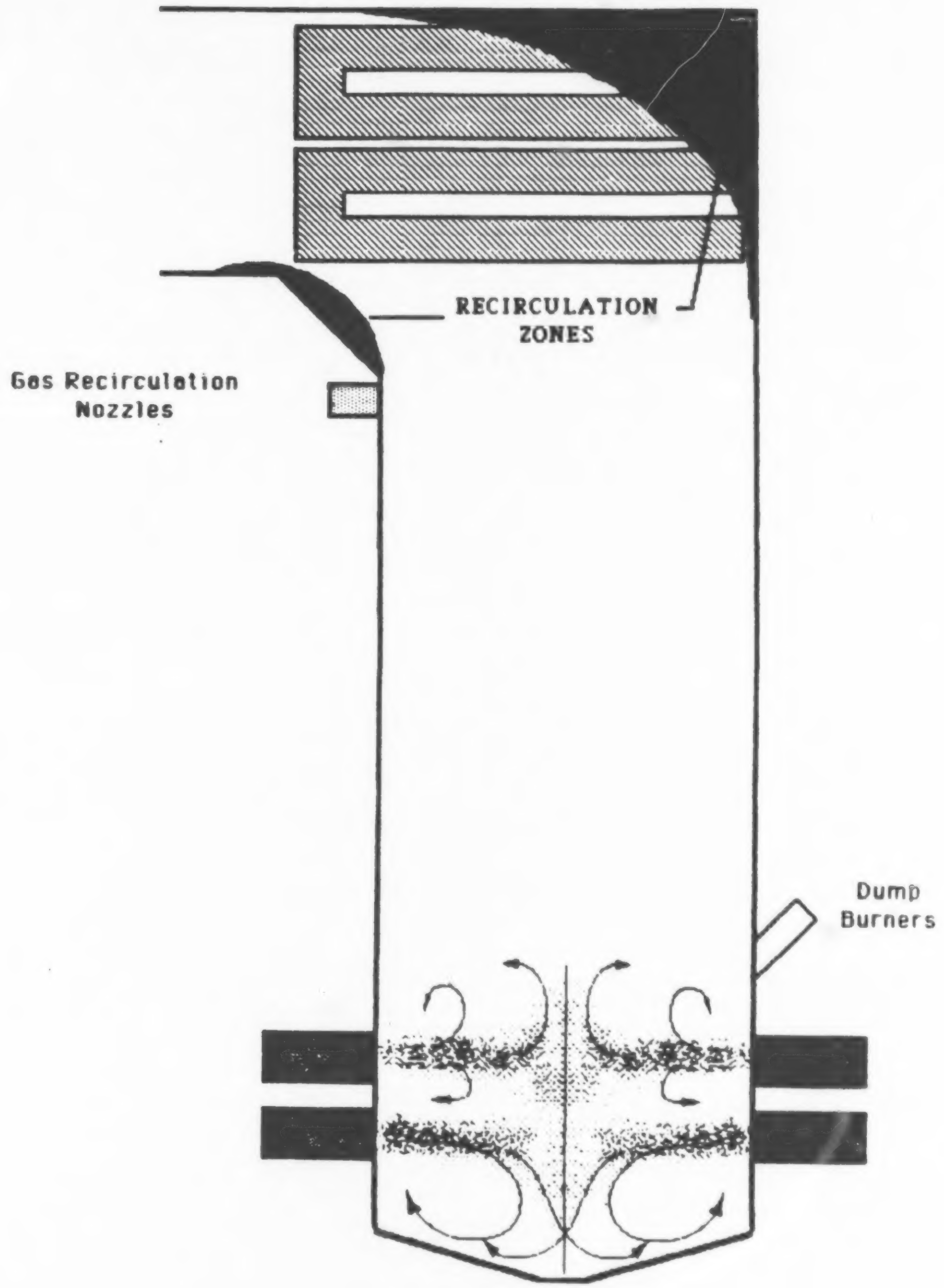

RECIRCULATION ZONES
Gas Recirculation Nozzles
Dump Burners

Figure 4-19. Flow Visualization Test Results; Main Burner Highlighted With Baseline Configuration

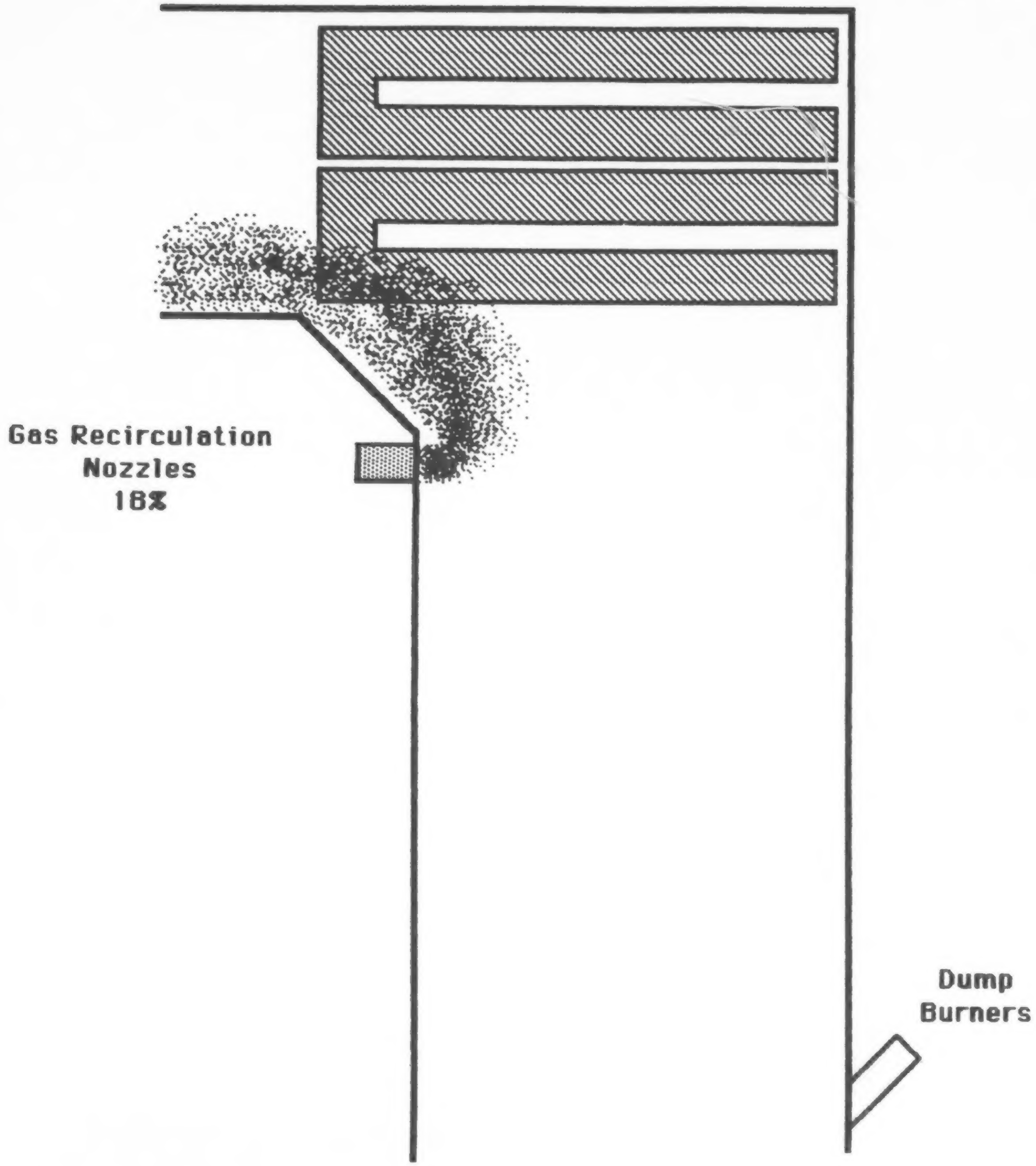

Gas Recirculation
Nozzles
18%
Dump
Burners

Figure 4-20. Gas Recirculation Nozzle Flow Visualization Test Results, Upper Gas Recirculation Highlighted With Baseline Configuration

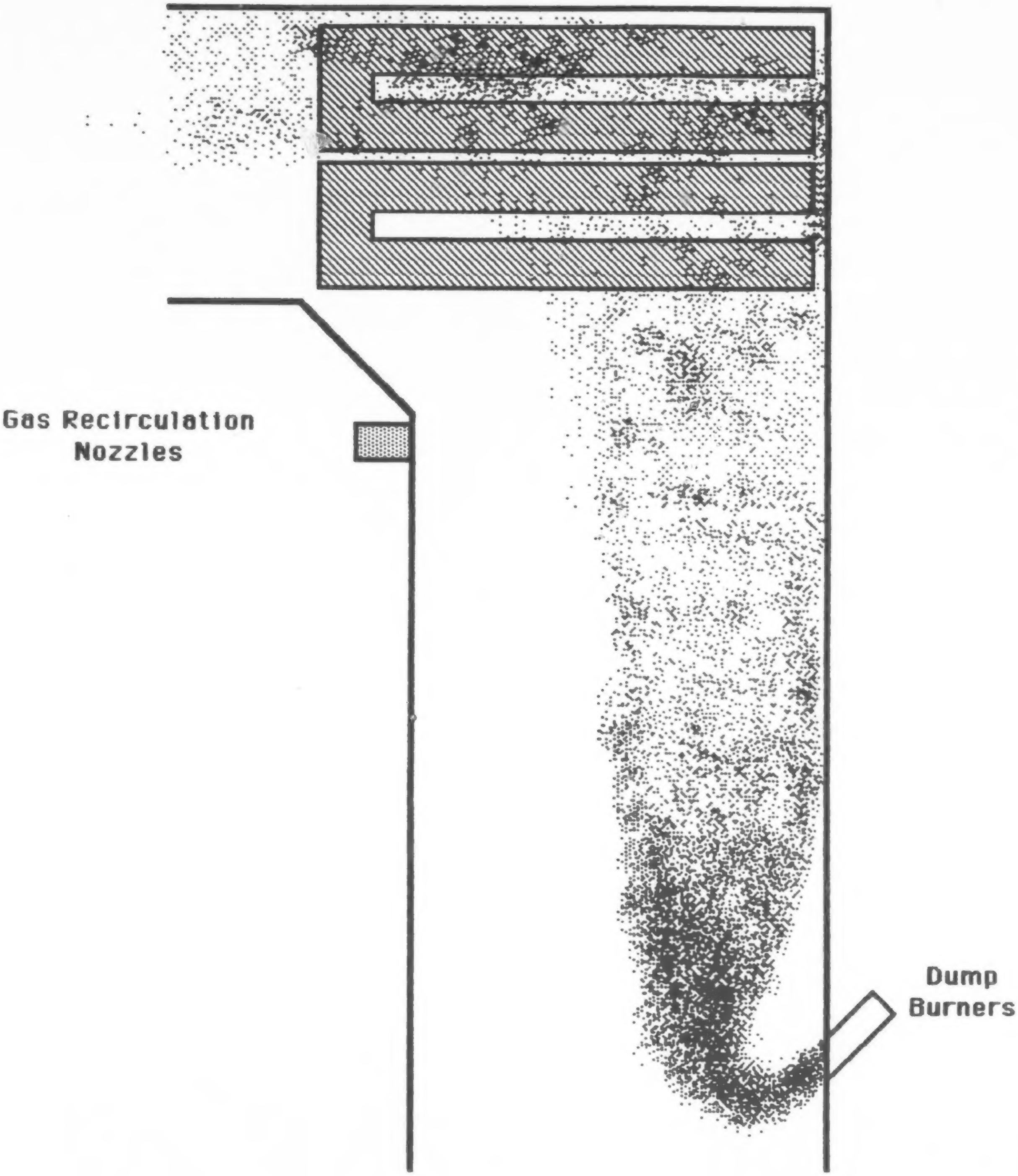

Gas Recirculation Nozzles
Dump Burners

Figure 4-21. Dump Burner Flow Visualization Test Results With Baseline Configuration

At the entrance to the superheater section of the unit the gasses had expanded to fill approximately 50% of the furnace depth, from the front wall to the centerline of the unit. These gasses attached to the front wall but expanded to the entire unit width.

A single quantitative test plane of three-dimensional velocity data was obtained from the flow model. Figure 4-22 identifies the placement of this test plane which was located at the entrance to the reburn fuel injection zone. Figure 4-23 presents the results from this traverse where it can be clearly seen that the axial flow field at this location was essentially uniform being only slightly higher in the center of the furnace. A depression at the centerline of the front wall of the furnace corresponds to the downward flow from the dump burners. Figure 4-24 shows the horizontal velocity vectors on the test plane. The vectors on this plot indicate that the flow was basically directed from the center of the unit towards the walls. This supports the observations made during the flow visualization tests which indicated that the flow from the primary fuel and air nozzles on opposite sides of the furnace impacted in the center of the unit and recirculate back to the walls.

REBURN SYSTEM FLOW MODEL TESTING

Using the jet modeling criteria discussed earlier, simulated reburn fuel and burnout air injection nozzles were fabricated and installed on the furnace flow model. Reburn system configurations were tested in two phases. The first phase evaluated the performance of the reburn fuel injection system without a burnout air system in operation. The second phase evaluated the

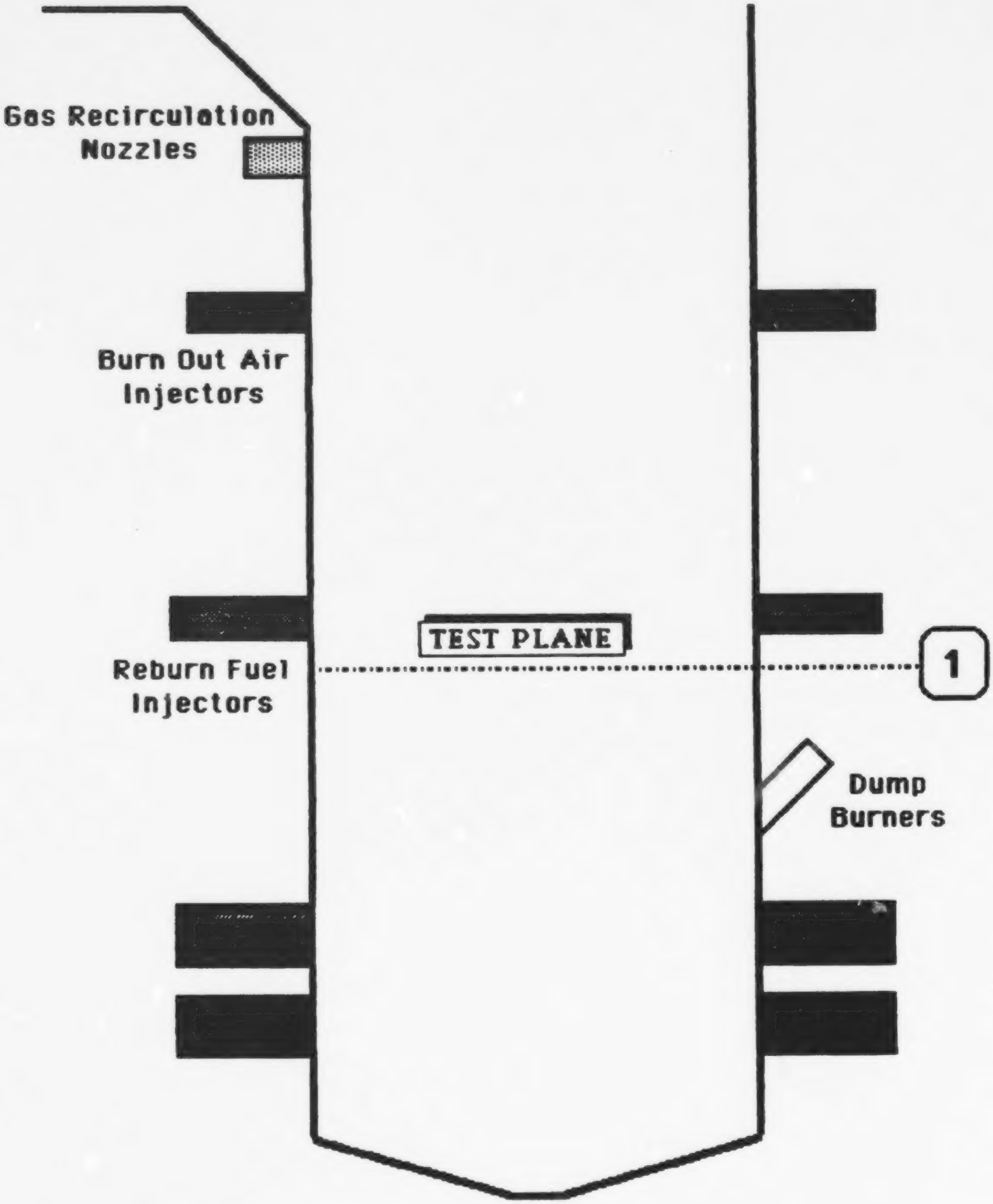

Gas Recirculation Nozzles
Burn Out Air Injectors
TEST PLANE
1
Reburn Fuel Injectors
Dump Burners

Figure 4-22. Test Plane Location

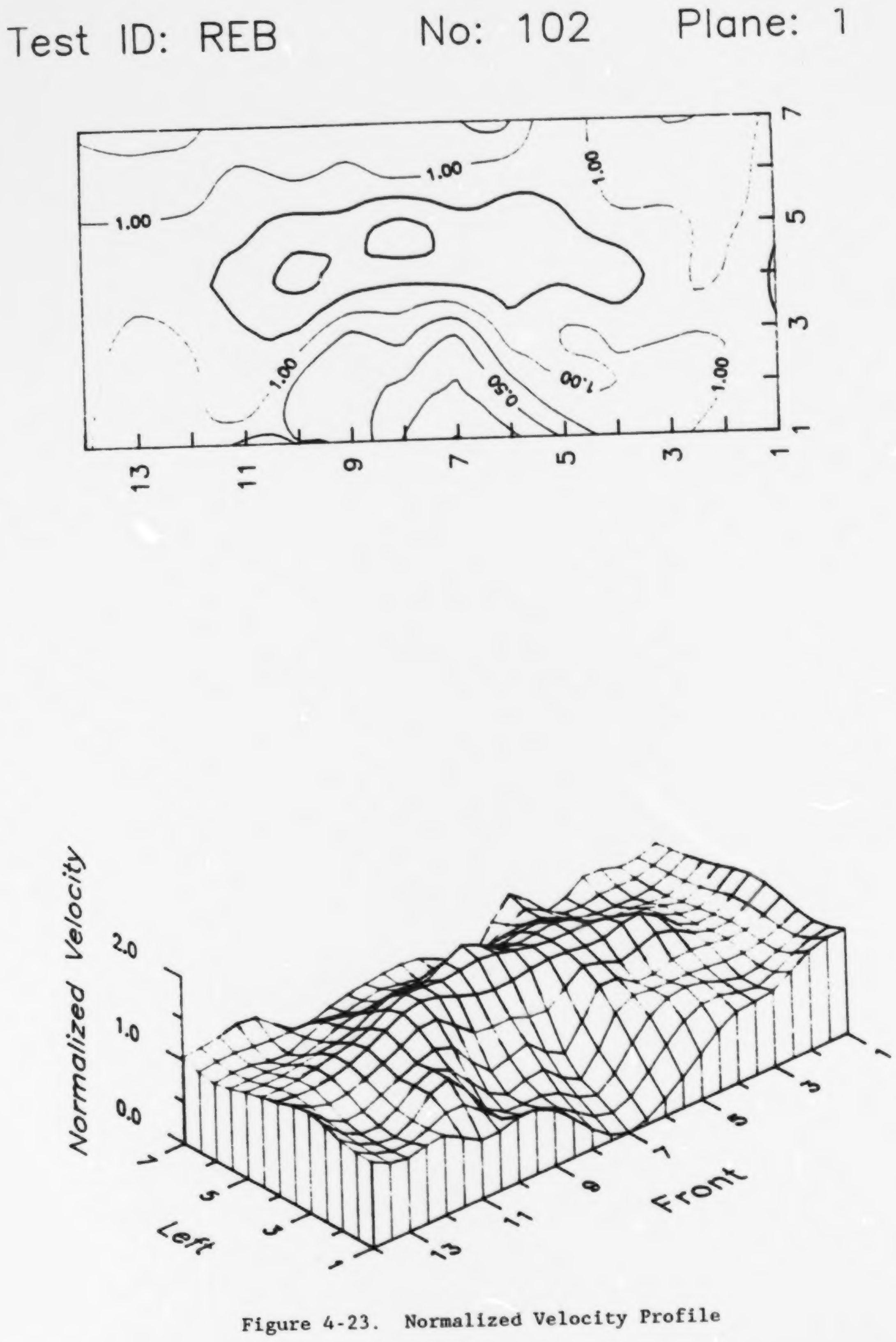
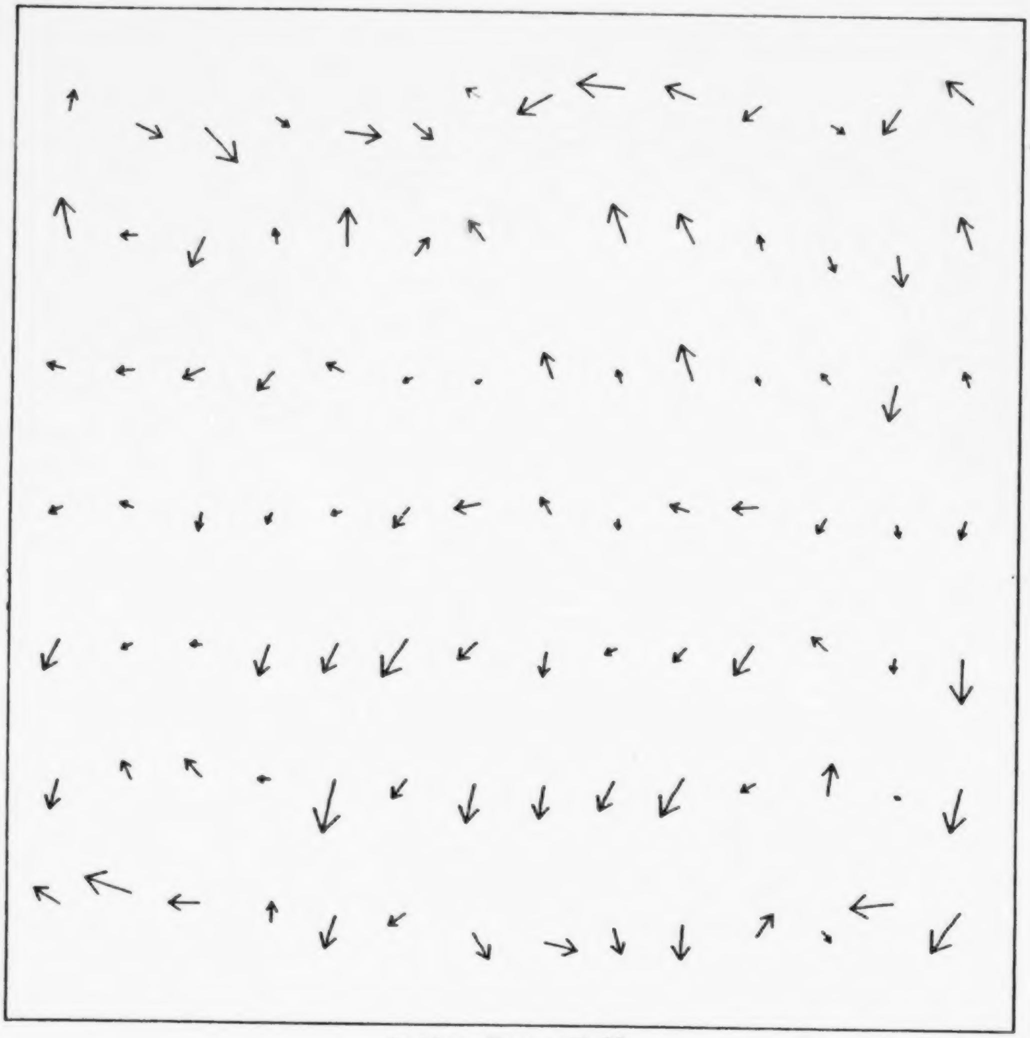


Figure 4-23. Normalized Velocity Profile

Test #: 102

Test Plane: 1

Test Date: 6/21/89



Scale : → EQUALS AVG.VEL. 16.25 FT/SEC

Figure 4-24. Velocity Vectors

performance of burnout air injection systems with the best performing reburn fuel system from the phase one efforts. The test matrices for both phases, previously presented in Table 4-1, were identical in terms of configuration, geometry and injection velocities. The only difference between these matrices were the total system flow rate and required nozzle diameters. The results of these tests are discussed in the next three sections. As will be detailed later, the performance of both the reburn fuel and burnout air injection systems were found to be nearly identical with any differences due primarily to the physical geometry around the injection location. The first section will therefore discuss these common traits. The following two sections will discuss the individual differences found between the reburn and burnout systems.

Each injection system was evaluated through the use of flow visualization techniques, using smoke as the tracer media. The results of each test were recorded on color video tape. Each injection system was evaluated at two vertical tilts angles, 0° and -30°. It was from the results of these thirty six (36) tests that recommendations for candidate Ladyzhinskaya reburn system configurations and injection velocities were made.

Combined Reburn System Flow Visualization Test Results

The flow visualization tests evaluated the penetration and dispersion performance of thirty six (36) different reburn fuel and burnout injection configuration/velocity combinations within the furnace. Each configuration was evaluated at 0° and -30° tilt and at injection velocities simulating 146, 183, and 229 ft/sec. (45, 56 and 70 m/sec).

The flow visualization tests and velocity mapping that was performed on the baseline furnace configuration indicated that the flow fields within the reburn and burnout zones of the unit were fairly uniform, both side-to-side and front-to-back. This type of environment was ideal from an injection standpoint because of the lack of recirculation zones, which could transport injected material into unfavorable areas of the furnace, and makes the job of uniformly dispersing the reburn fuel easier.

It was found that the penetration and dispersion performance of the individual jets changed as a function of the six wall locations. The trajectories shown in Figure 4-25 represent jets emanating from each of the locations on the front wall of the unit. It can clearly be observed in this figure that the center most jets (jets 3 and 4) penetrated significantly further into the unit than the other jets. This is due to the fact the two sets of centerline nozzles are located very close to each other and act as one larger diameter jet. The jets located adjacent to the side walls (jets 1 and 6) on the other hand, were observed to attach to the walls and had their level of penetration significantly reduced. Only the middle nozzles (jets 2 and 5) were unencumbered and operated very close to the predictions discussed earlier. Because of this difference in overall jet penetration it is recommended that dampers be installed upstream from each of the nozzles such that the flow into the centerline nozzles can be throttled back and redistributed to the side wall jets. In this manner, the penetration of each of the injectors can be optimized to the field conditions.

As predicted with the jet penetration calculations, injection configurations consisting of twelve (12) individual nozzles penetrated further into the

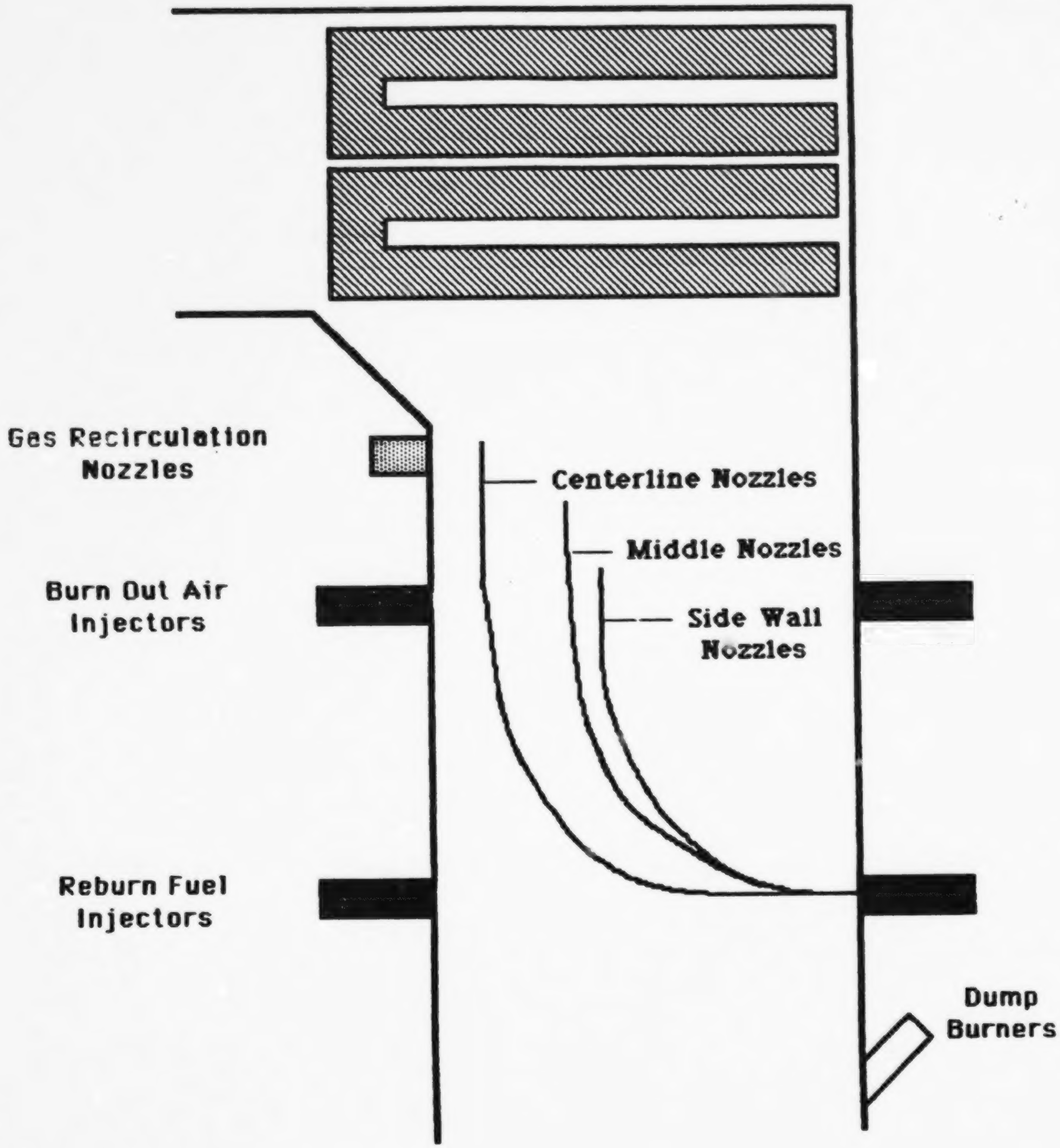

Gas Recirculation Nozzles
Centerline Nozzles
Middle Nozzles
Burn Out Air Injectors
Side Wall Nozzles
Reburn Fuel Injectors
Dump Burners

Figure 4-25. Penetration vs. Nozzle Location

furnace then injection configurations consisting of twenty-four (24) nozzles when they operated with the same injection velocity and mass flow rate. To maintain the same injection velocity and mass flow rate, the open area of the nozzles had to be doubled when the number of nozzles was reduced by half. This observation is shown in Figure 4-26.

For all injection scenarios, the side-to-side dispersion of injected material was found to be adequate, Figure 4-27. Material injected from the two nozzles located adjacent to the side walls experienced heavy jet attachment to these walls. This phenomenon is detailed in Figure 4-28. Because this jet attachment is unwanted, it is recommended that the side wall injection nozzles be given yaw capability away from the wall. Or alternatively, they should be designed to inject at least 18° away from the walls.

It was found that the pantleg arrangement provided higher levels of dispersion than the straight through nozzles and that the combined pantleg upper and straight-through lower arrangement was an effective penetration and dispersive design. The pantleg nozzle was responsible for the dispersion of material near the front and/or rear walls of the unit while the straight-through nozzles accounted for the penetration to and dispersion of material in the center of the unit.

Reburn Fuel System Flow Testing

Figure 4-19 presents the jet trajectories of three reburn fuel injection jet velocities for the configuration where twelve (12) individual injection nozzles were located on both the front and rear walls for a total of

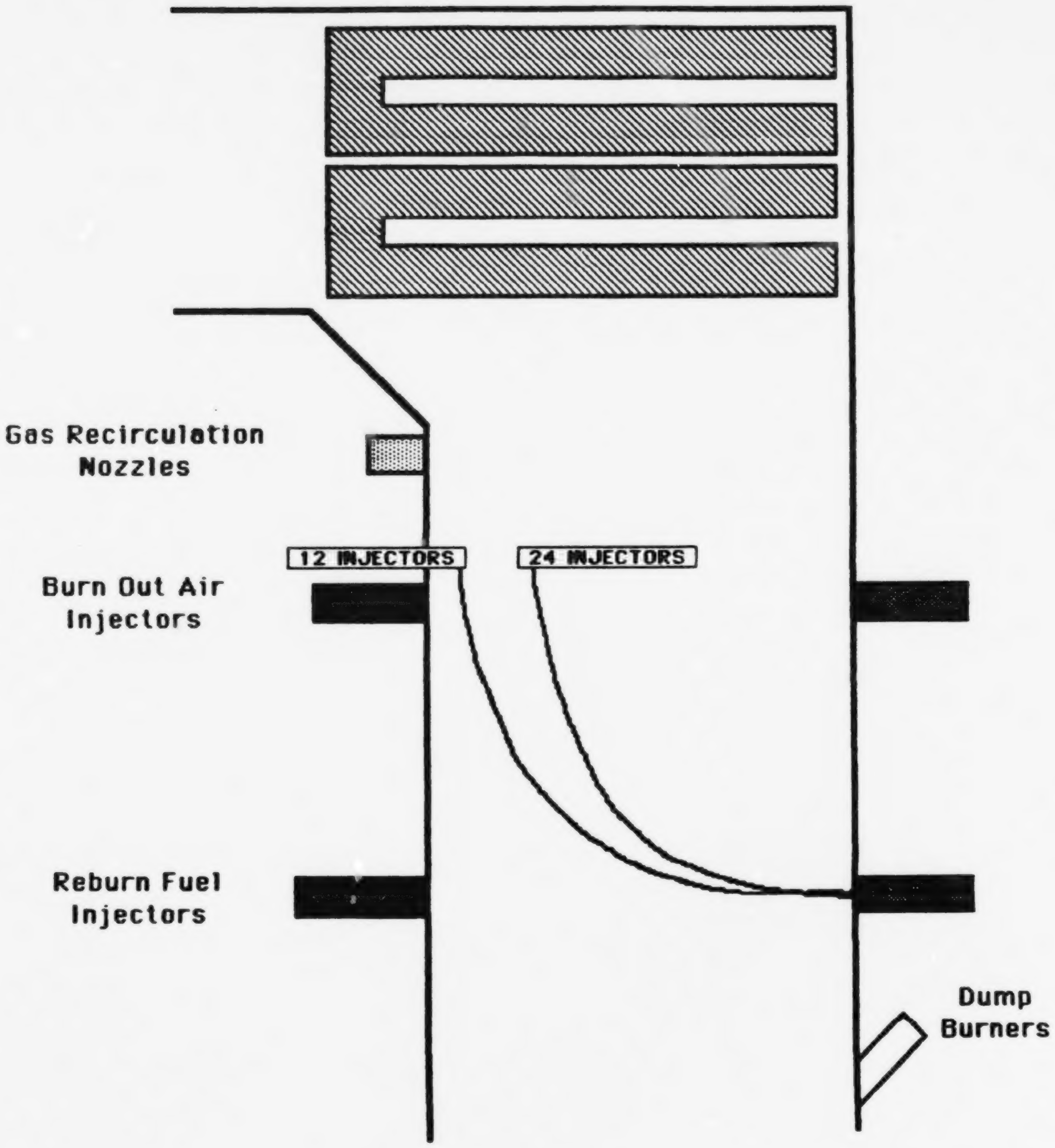

Gas Recirculation Nozzles
12 INJECTORS
24 INJECTORS
Burn Out Air Injectors
Reburn Fuel Injectors
Dump Burners

Figure 4-26. Flow Visualization Test Results, Reburn Fuel Injectors Number vs. Penetration

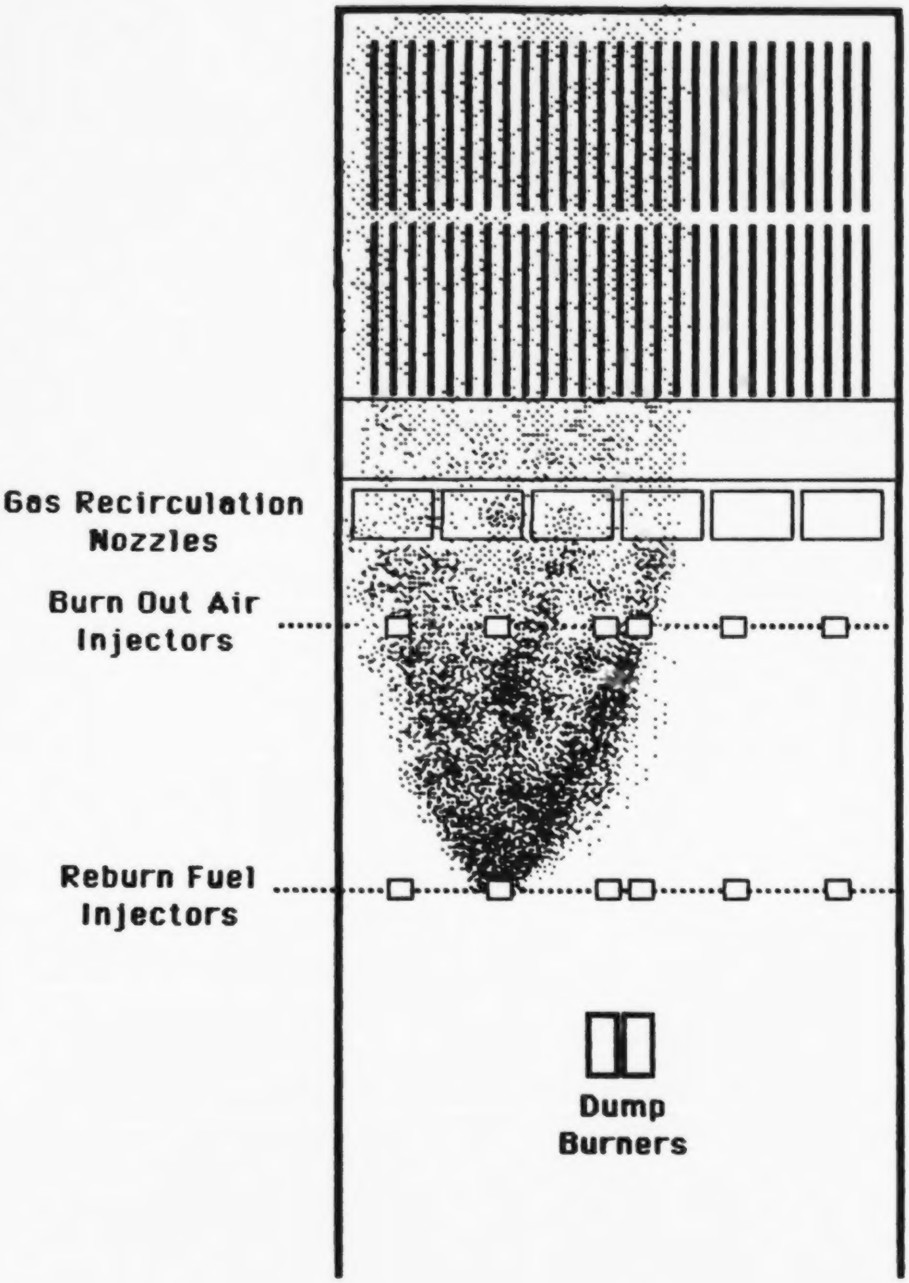

Gas Recirculation Nozzles
Burn Out Air Injectors
Reburn Fuel Injectors
Dump Burners

Figure 4-27. Flow Visualization Test Results, Reburn Fuel Injectors Lateral Dispersion With Middle Nozzles

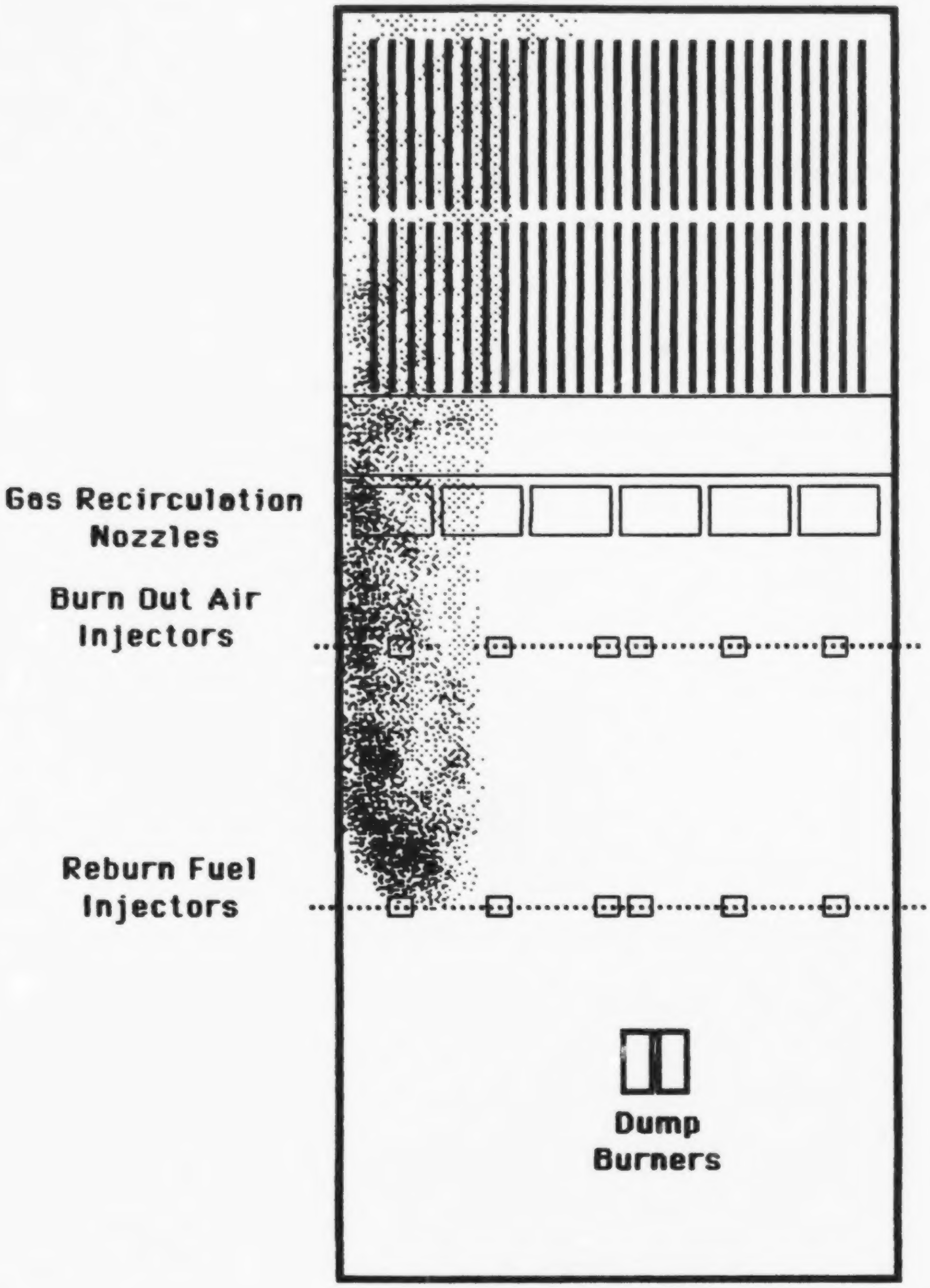

Gas Recirculation Nozzles
Burn Out Air Injectors
Reburn Fuel Injectors
Dump Burners

Figure 4-28. Flow Visualization Test Results, Reburn Fuel Injectors Lateral Dispersion With Side Wall Nozzles

twenty-four (24) individual injection nozzles. Injection vertical tilt angle was 0°. The trajectory lines shown represent the leading edge of the visualized jet. For the sake of clarity, only the trajectories from the front wall have been shown. The trajectories from the rear wall were similar but in the opposite direction. It can be seen in this figure that 146 ft/sec (45 m/sec) injection velocity is sufficient to have the reburn fuel jet penetrate slightly past the centerline of the unit. Remembering that there is another set of injectors located on the rear wall injecting at the same time, penetrating of slightly past the centerline is considered ideal in terms of providing a uniform a fuel distribution. The other injection velocities over penetrated and impacted the opposite wall of the furnace. The 183 ft/sec (56 m/sec) jet impacted at a point just slightly below the burnout air injection elevation. The 229 ft/sec (70 m/sec) jets impacted the opposite wall just slightly above their point of injection. For both of these injection velocities, interactions with the jets from the opposite wall caused the amount of penetration to and the location of impact on the opposite wall to change. What has been reported here are the most common or average flow patterns.

Because of the jet-to-side wall and jet-to-jet interactions discussed earlier, the trajectories shown in Figure 4-29 represents the trajectories of the middle or second set of nozzles from each side wall of the unit. This location was chosen for presentation because they, and their mirror image on the other side of the furnace, were the only jets that were not in some way encumbered by interactions with the side wall of the furnace or other closely located jets and therefore clearly show the average performance of all the injectors involved in the system.

1 FOOT (FT) = .3048 METERS (M)

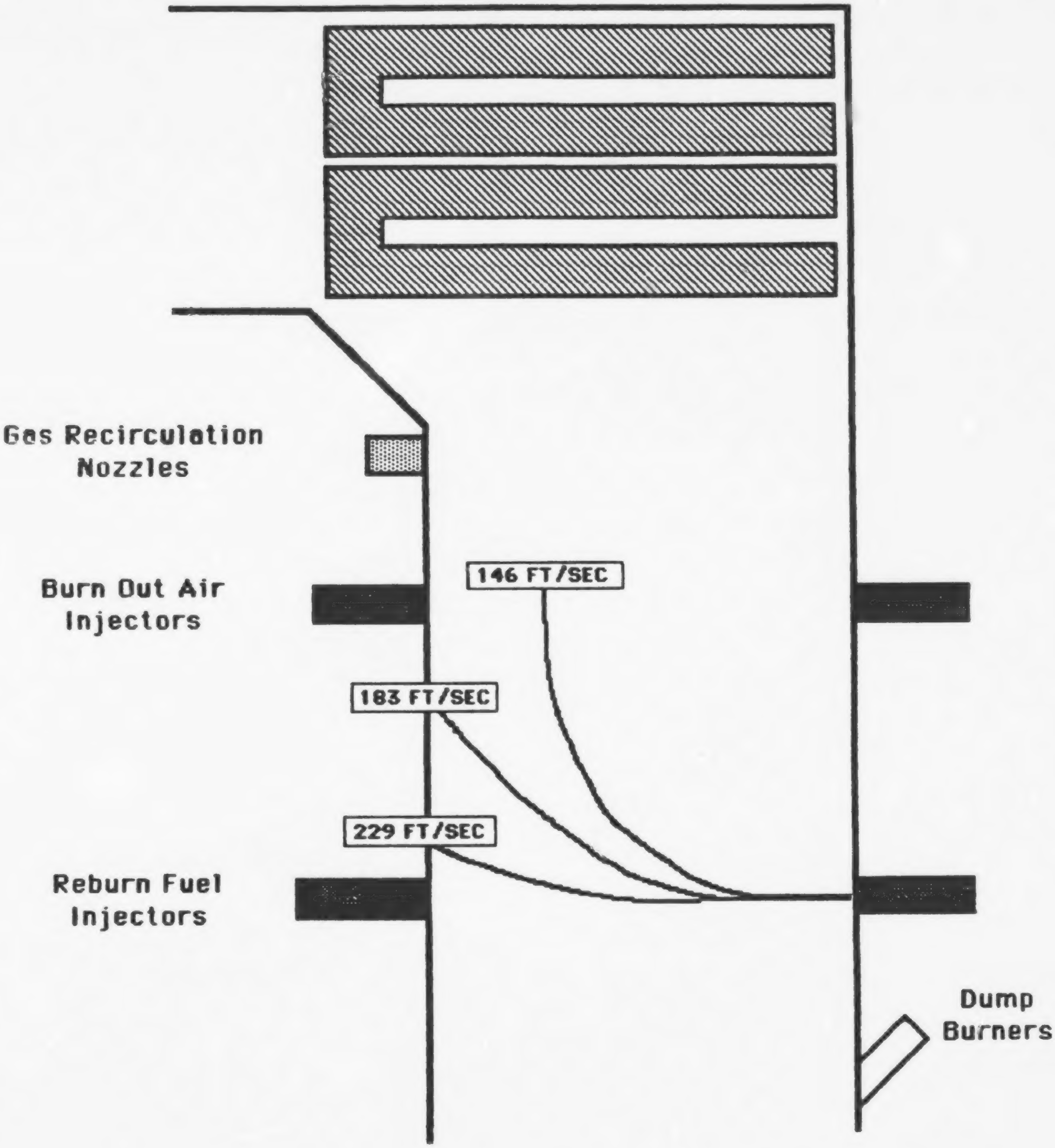

Gas Recirculation Nozzles
Burn Out Air Injectors
146 FT/SEC
183 FT/SEC
229 FT/SEC
Reburn Fuel Injectors
Dump Burners

Figure 4-29. Flow Visualization Test Results, Reburn Fuel Injectors Penetration vs. Velocity

Figure 4-30 shows the dispersion pattern for the 146 ft/sec (45 m/sec) reburn fuel jet at 0° tilt. This jet penetrates almost horizontally to the center of the unit before it turns upward. Dispersion was found to be very good in all but a small area located along the wall just downstream of the injection point. This particular area was devoid of injected material. The jets quickly dispersed in both the side to side-and-front to back directions. As shown in Figure 4-30 the jet has expanded and has attached to the front wall of the unit before the burnout air injection elevation. The jets from the front and rear wall do not mix much even by the entrance to the economizer sections of the furnace. The jets from the front wall exit the furnace near the roof of the unit while those from the rear wall exit just over the arch. This is shown in Figure 4-31. Note on this figure that the injected material does not immediately mix with the material entering the furnace from the upper furnace flue gas recirculation nozzles, the area above the arch remaining free of reburn fuel. Note, also, that on occasion some material injected from the front wall, at both 0° and -30° tilt, was recirculated into the main combustion zone of the unit due to interaction with the dump burner flow.

For all configurations and injection velocities, vertically down tilting the nozzles significantly increased the amount of dispersion but not the cross furnace penetration. At an injection velocity of 146 ft/sec (45 m/sec), for example, the penetration did not appear to increase more than a few percent. Angling the injection nozzles downward did, however, result in some of the reburn fuel being intermittently recirculated into the combustion zone of the furnace. This observation is shown in Figure 4-32.

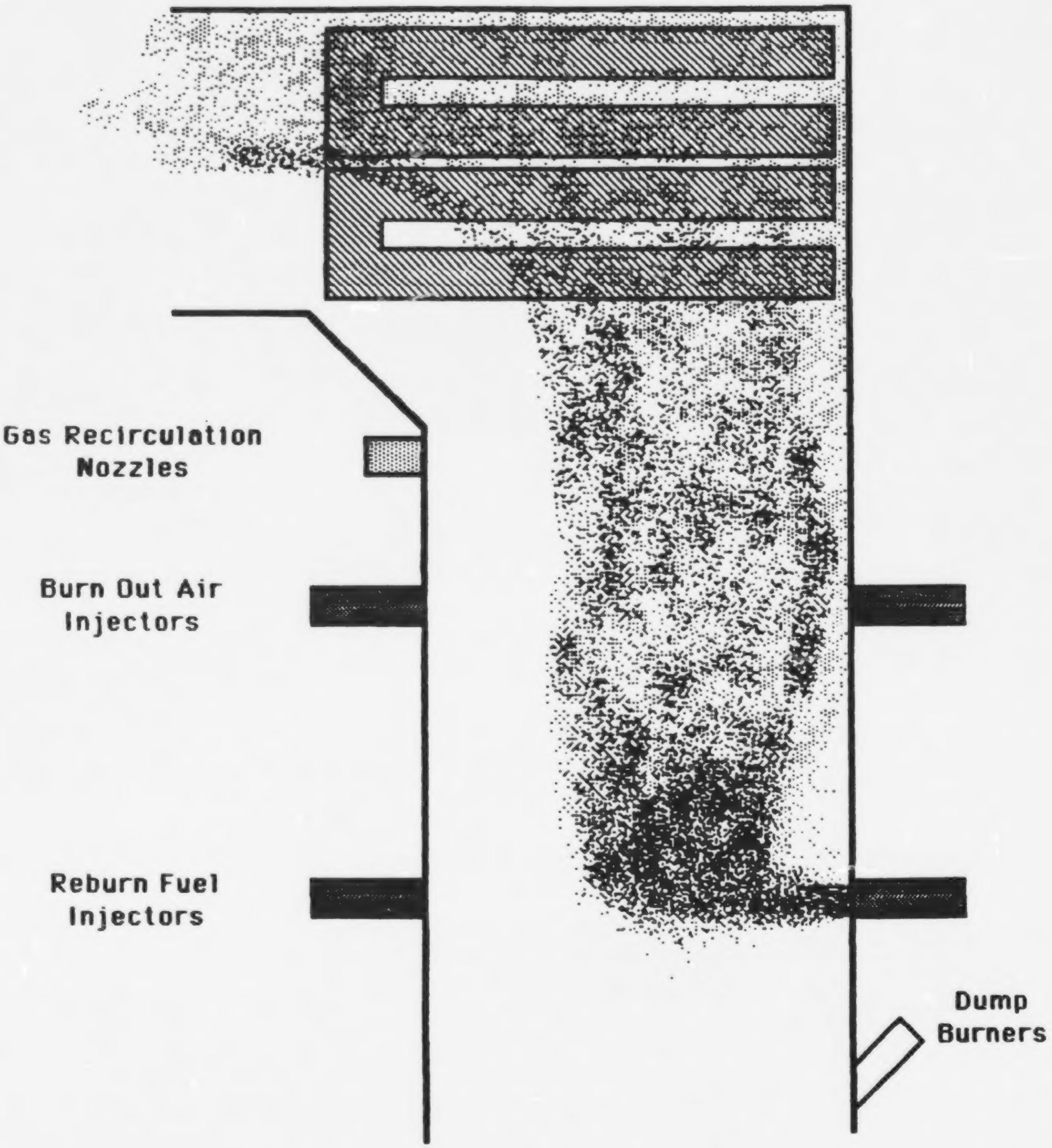

Gas Recirculation Nozzles
Burn Out Air Injectors
Reburn Fuel Injectors
Dump Burners

Figure 4-30. Reburn Fuel Injectors Visualization Test Results, Front Wall

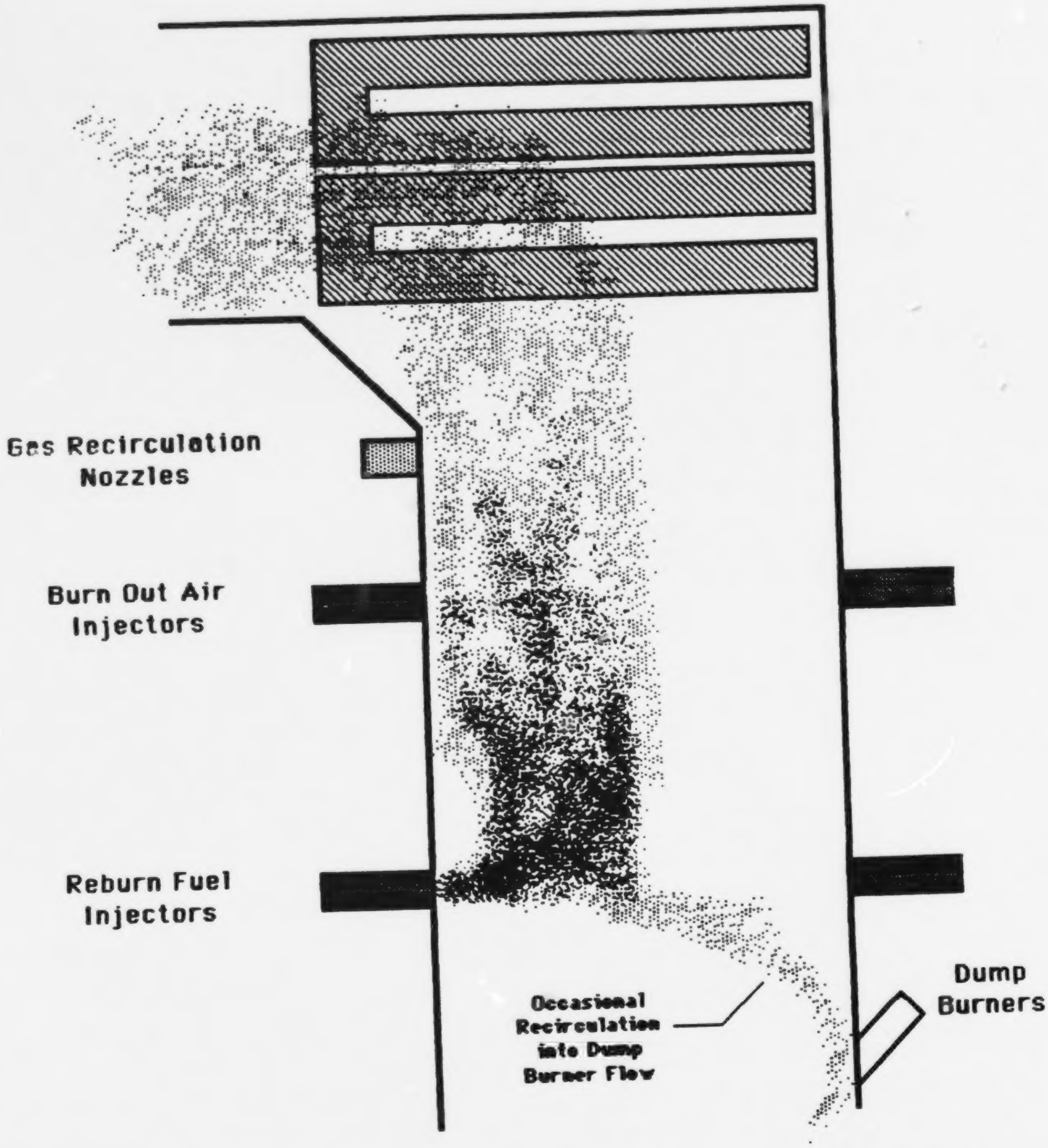

Gas Recirculation Nozzles
Burn Out Air Injectors
Reburn Fuel Injectors
Dump Burners
Occasional Recirculation into Dump Burner Flow

Figure 4-31. Reburn Fuel Injectors Visualization Test Results, Rear Wall

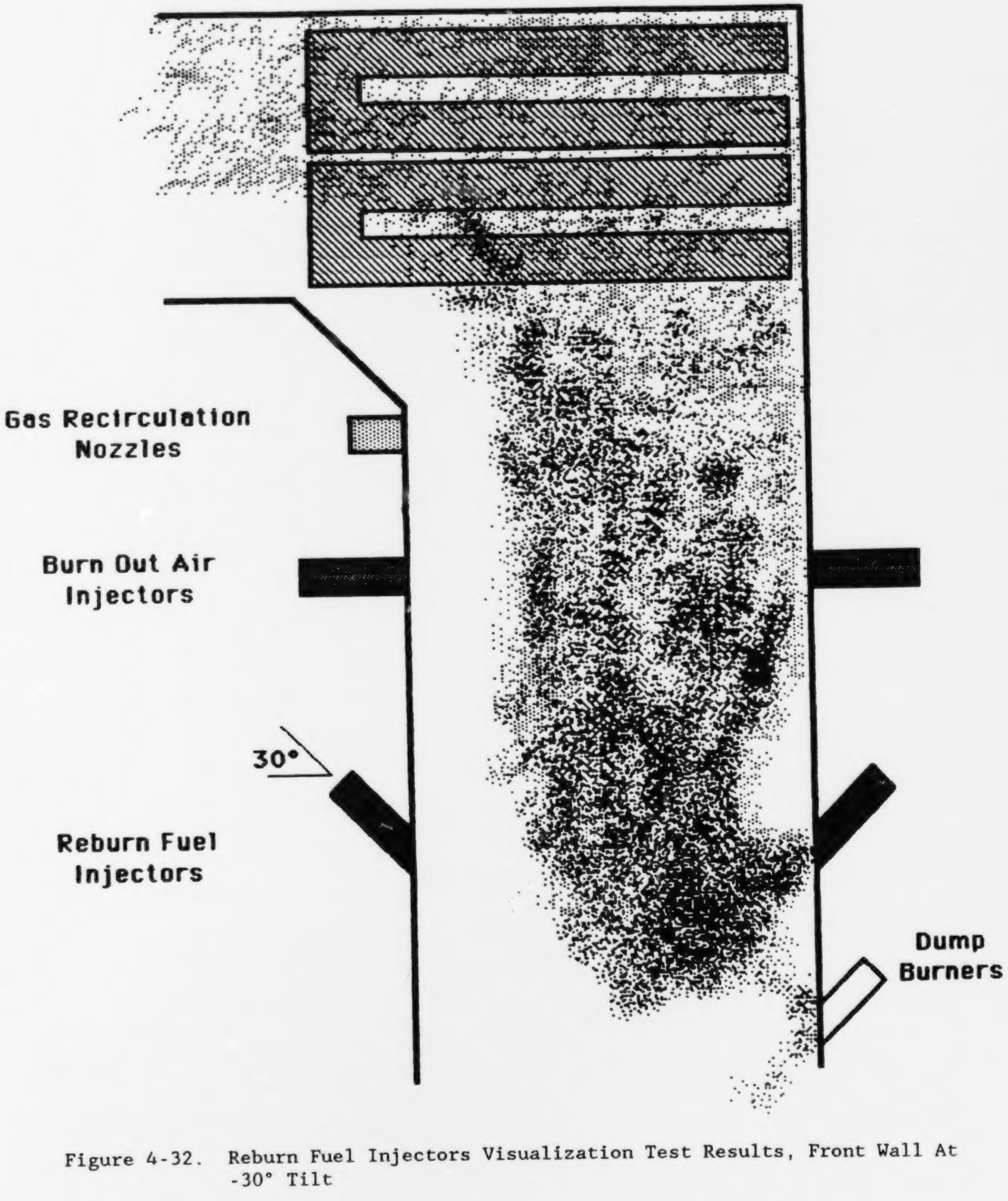

Gas Recirculation Nozzles
Burn Out Air Injectors
30°
Reburn Fuel Injectors
Dump Burners

Figure 4-32. Reburn Fuel Injectors Visualization Test Results, Front Wall At -30° Tilt

Down tilting did result in increased downward penetration and thus increased the residence time of the injected fuel. Down tilting the injection nozzles therefore should be considered as a means of increasing the overall flexibility of the injection system. Injecting downward may be useful as a method of optimizing the reburn process if the furnace load should change and the temperature profile within the injection zone should change.

Burnout Air System Flow Testing

The performance of the burnout air system was almost identical to that observed for the reburn fuel system. The major difference in the injection performance was in the penetration of the jets for a given velocity. Two reasons for this have been identified. First, the mass flow rate of the burnout air is 70% higher than that for the reburn fuel. This, in itself, under identical cross flow conditions, would account for a 30% increase in the penetration of the jet. Secondly, the aerodynamics in the burnout air injection zone are more conducive to higher levels of penetration because of the change in flow direction cause by the turn at the top of the unit. Simply put, the jets on the front wall are injecting into a flow field that is in the process of changing from cross flow to coaxial.

Figure 4-33 presents the trajectories of three burnout air jets simulating 146, 183 and 229 ft/sec. (45, 56 and 70 m/sec). For this case, these were six windbox locations on both the front and rear walls for a total of twelve locations and representing twenty four (24) injectors in operation. Twelve (12) on the front wall and twelve (12) on the rear wall. The trajectories from the jets located on the rear wall were omitted on the figure for the sake of clarity. Injection at 229 ft/sec (70 m/sec) resulted in the jet

1 FOOT (FT) = .3048 METERS (M)

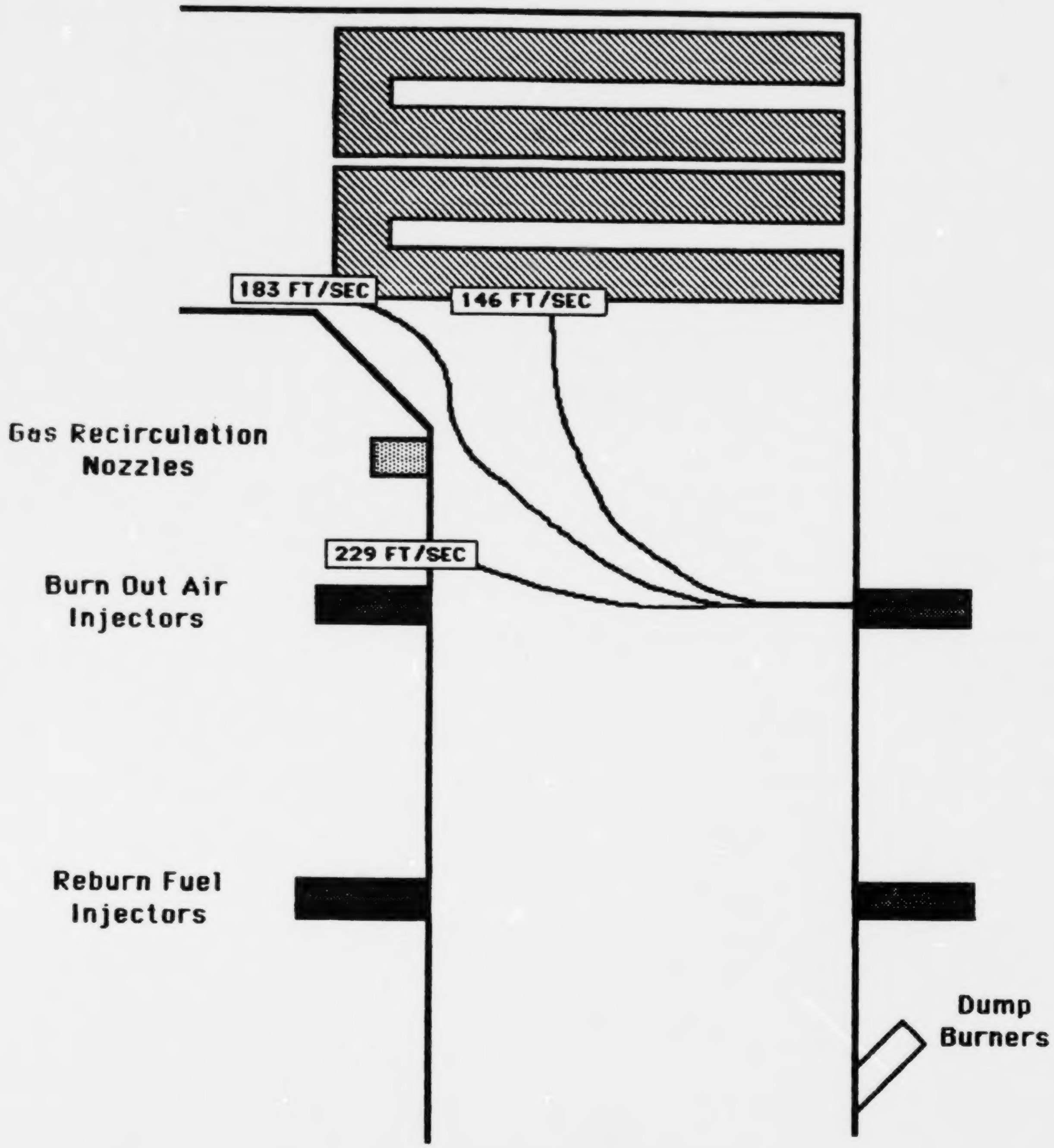

183 FT/SEC
146 FT/SEC
Gas Recirculation Nozzles
229 FT/SEC
Burn Out Air Injectors
Reburn Fuel Injectors
Dump Burners

Figure 4-33. Burnout Air Injectors Flow Visualization Test Results, Penetration vs. Velocity

impacting the opposite wall of the unit almost directly across from the point of injection. At 183 ft/sec (56 m/sec) the jets missed the rear wall and exited the unit low above the arch. At 146 ft/sec (45 m/sec) the jets quickly turned upward and did not provide sufficient penetration into the center of the furnace. Injection from rear wall did not result in levels of penetration nearly as high as those from the front wall because they were injecting into a flow field that was approaching counter flow.

It is recommended that the design injection velocity range of the burnout air system be between 183 ft/sec (56m/sec) and 229 ft/sec (70 m/sec). While injection at 229 ft/sec (70 m/sec) from the front wall resulted in the jets impacting the rear wall of the unit, extremely rapid dispersion of the burn out air is required because of the relatively short residence time of the material before it enters the superheater section of the furnace. In general, 183 ft/sec (56 m/sec) looked adequate but a significant portion of the available burnout air zone was felt to be under utilized based on the flow visualization tests conducted.

As with the reburn fuel system, it is also recommended that each of the burnout air nozzles be fitted with a flow control damper as it will be necessary to divert flow away from the centerline nozzles to the lessor penetrating sidewall nozzles.

Summary of Isothermal Physical Flow Modeling Results

Isothermal flow modeling was used to develop reburn fuel and burnout air injection configurations for the preliminary reburn system design. From these studies, the following recommendations are made:

1. Because of the need for rapid dispersion of both the reburn fuel and burnout air, twelve (12) nozzles of each respective type will be required. For the reburn injectors, six (6) nozzles will be located on the front wall and six (6) on the rear wall. Similarly, for the burnout air, six (6) nozzles will be located on the front wall and six (6) will be located on the rear wall.

2. The reburn fuel nozzle configuration should be designed to achieve a jet velocity at the nozzle exit of 146-183 ft/sec (45-56 m/sec).

3. The burnout air nozzle configuration should be designed 59 achieve a jet velocity at the nozzle exit of 183-229 ft/sec (56-70 m/sec).

4. -30° down tilt will significantly increase the dispersion of the injected material. This capability should therefore be incorporated into the design of both the reburn fuel and burnout air injection systems.

5. The pantleg/straight-through combined nozzle design was effective in creating both high levels of dispersion and penetration.

6. Because of jet attachment to the side walls of the furnace, those injection nozzles located adjacent to the walls should have the ability

to yaw away from them. Or alternatively, the nozzles should be designed to inject at least 18° away from the walls.

7. The center jets, because of their close proximity to each other, act as one larger area jet and over penetrate. Each nozzle should have the ability to be dampered to redistribute their flow to other nozzles requiring additional penetration.

SECTION 5

PRELIMINARY REBURN SYSTEM DESIGN

INTRODUCTION

The objective of this task was to establish the preliminary system design configuration and finalize injector locations for the Ladyzhinskaya steam generator.

The approach used to meet this objective was to first establish initial locations and configurations for the reburn fuel/FGR and burnout air subsystems, including shape, flowrate and nozzle velocities. These selections were based on the established reburn system design criteria, physical inspection of the boiler and an initial review of the boiler arrangement as presented on the boiler drawings provided during the site inspection.

These initial selections provided the basis for the examinations conducted during the physical flow modeling. As a result of the physical flow modeling, the final process flow calculations and other design considerations (such as location and potential arrangements for the connecting FGR and air ductwork) the selected locations and configurations were revised as required. From these revised selections reburn system general arrangement (GA) drawings were developed.

DESIGN ASSUMPTIONS

The physical configuration and operation of the Ladyzhinskaya steam generator was well defined during the plant inspection and in the information package and drawings provided by the Soviet side such that all major inputs to the design of the reburn system were available. However, it was necessary to make several minor design assumptions at several stages of the reburn system design to proceed with the design. These assumptions, as presented below, (see also Tables 5-1 and 5-2) were subsequently presented to and discussed with the Soviets and all were either confirmed or considered to have minor impact on the design. Of the seven assumptions listed below the first three relate to the physical flow modeling and would thus impact the accuracy, thereof, and the last four pertain to the reburn system design.

1. Flue Gas Recirculation Compartment Configuration - Limited information was available on the configuration of the upper furnace FGR compartments located at elevation 115 feet (35.1 meters). Scaling of the available drawings resulted in a calculated FGR jet velocity of approximately 33 ft/s (10 m/s). The flow modeling was based on this and subsequently showed poor penetration and dispersion of the upper furnace FGR. Discussions with the Soviet representatives subsequently stated a jet velocity of approximately 66 ft/s (20 m/s) would have more accurately represented current conditions. However, they agreed with the flow model results and in addition stated that similar results existed with the actual 66 ft/s (20 m/s) jet velocity. In addition, the Soviets were planning to modify the FGR compartments and upper furnace arrangement (addition of aerodynamic arch or "nose") to improve the FGR operation.

Table 5-1. Preliminary Reburn System Design Assumptions

1. UPPER FLUE GAS RECIRCULATION NOZZLE CONFIGURATION - EXIT FREE AREA/HEIGHT/WIDTH EXIT DIMENSIONS (C-E SCALED DIMENSIONS FROM SOVIET DRAWINGS).

2. PURPOSE FOR UPPER FLUE GAS RECIRCULATION IN UNIT (C-E PROPOSES TO DIRECT A PORTION OF THIS FLOW TO THE REBURN FUEL INJECTORS).

3. MAIN COAL BURNER VANE CONFIGURATION (C-E SCALED VANE DIMENSIONS/SWIRL ANGLE FROM SOVIET DRAWINGS).

4. C-E HAS ASSUMED THAT EXISTING FUEL PIPING AND AIR DUCTING IS SYMMETRIC ABOUT LEFT AND RIGHT SIDE OF BOILER CENTERLINE (NON-SYMMETRY MAY RESULT IN PIPE/DUCT INTERFERENCES).

5. UPPER FLUE GAS RECIRCULATION DUCTWORK NOT DETAILED ON SOVIET DRAWINGS (COULD PRESENT INTERFERENCES WITH BURNOUT AIR INJECTOR DUCTWORK).

6. UPPER ("DUMP") BURNER EFFECTIVE INJECTION ANGLE (C-E ASSUMED MINUS 30° BASED ON SCALED SOVIET DRAWING INFORMATION).

2. Main Coal Burner Swirler Configuration - From the available main burner general arrangement drawings it was possible to scale the burner configuration for use in the physical flow model. However, some of the burner details were not readily apparent on the provided drawings and thus it was necessary to assume some information. In particular, it was necessary to scale the burner air swirler vane dimensions and angle. These assumptions were accepted by the Soviet side as representative of the actual arrangement.

3. Upper ("Dump") Burner Effective Injection Angle - From the available drawing information a minus thirty (-30°) degree injection angle was assumed. This was later confirmed.

4. Upper Flue Gas Recirculation (FGR) Usage - The assumption was made that upper furnace FGR was used at the Ladyzhinskaya boiler was used to modulate the furnace exit gas temperature (FEGT) and superheat and reheat steam and metal temperatures. For the proposed Reburn System a portion of the upper furnace FGR would be diverted to the reburn fuel injector assemblies. The above assumption was made to insure that the temperature control feature of the FGR was maintained with the Reburn System design. This assumption was confirmed by the Soviet side.

5. Symmetry of Existing Fuel Piping and Air Ducting About Furnace Left/Right Centerline - The available drawings presented half-views of the furnace, therefore, it was necessary to assume symmetry to develop the Reburn System general arrangement drawings without pipe/duct interferences.

6. Upper Flue Gas Recirculation Ductwork Configuration - It was necessary to assume the location and configuration of portions of the FGR ductwork because insufficient detail was available. This would only impact the system by necessitating the revision of the proposed burnout air system ductwork were interferences present.

The above stated assumptions were employed to develop reburn system general arrangement drawings. The reburn and burnout air windboxes and internal windbox compartment configurations were included in the preliminary GA's whereas any connecting ductwork was only presented in "phantom form" to reflect a proposed general location.

SELECTION OF REBURN FUEL AND BURNOUT AIR INJECTOR LOCATIONS

Based upon the provided boiler drawings, physical inspection of the Ladyzhinskaya boiler and review of the photographs from the unit inspection it was determined that access to the furnace sidewalls for reburn system components would require extensive pipe/duct modifications. Therefore, the program limited its analysis to reburn system components to be located on the front and/or rear furnace waterwalls.

The boiler waterwall was made up of 3 sections consisting of a lower, midwall and upper waterwall. Distribution headers were located between each section. For each section the waterwall tubes were arranged in a closely packed "S" shaped configuration. To minimize the impact of a Reburn System retrofit on boiler operation the proposed reburn fuel and burnout air windbox locations were matched to coincide with the "S" shape configuration (Figures 5-1 and

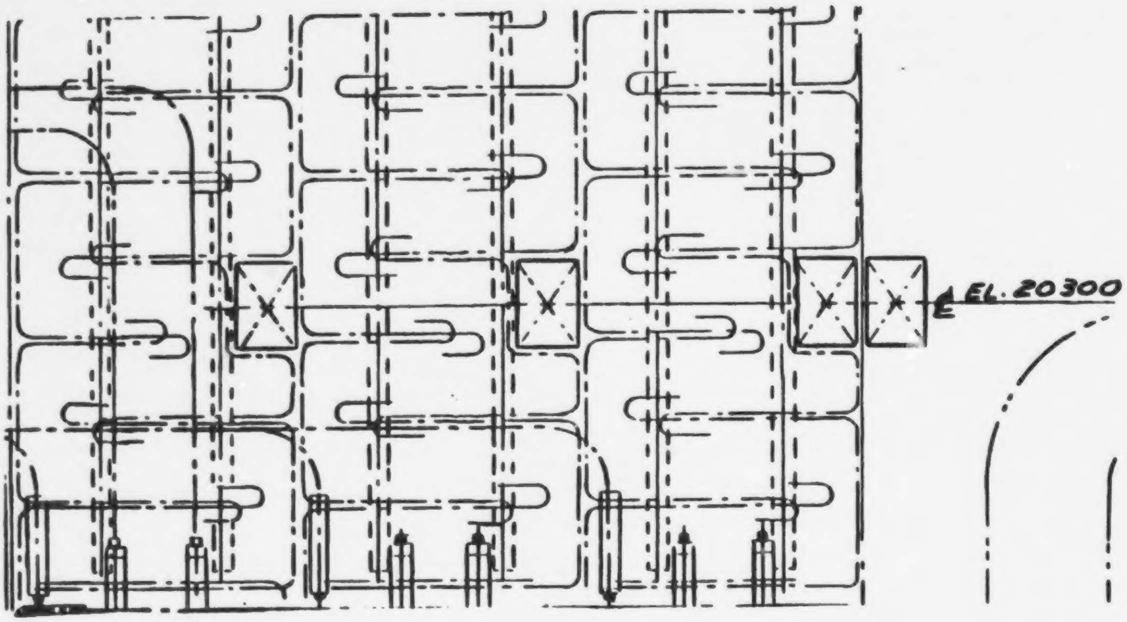


Figure 5-1. Example of Tube Modifications For Reburn Fuel Injector Installation

5-2). Across the front and rear waterwalls there were 6 sets of "S" shape tube bundles each approximately 9.5 feet (2.9 meters) wide and 7.9 feet (2.4 meters) high. Therefore, for the initial reburn fuel and burnout air injector locations six and twelve (multiple of six) locations across the front and/or rear wall, if required, were selected. (Several other arrangements were, also, initially looked at but did not show significantly different results that could justify the required increased complexity of the waterwall circuit modifications.)

The elevations selected for the reburn fuel and burnout air windboxes were based upon the reburn system design criteria (furnace gas residence time in each zone, combustion efficiency etc.) while taking into account potential interferences with other boiler equipment (pipes, ducts, headers, structural steel) (see Figures 5-3 and 5-4).

As stated previously, these initial selections were then parametrically evaluated in the physical flow model. From this examination it was determined that both front wall and rear wall injector locations consisting of 6 compartmented windboxes on each wall for both the reburn fuel injectors and burnout air injectors was optimal for mixing, penetration and dispersion.

REBURN FUEL AND BURNOUT AIR INJECTOR CONFIGURATIONS

Based upon the flow modeling it has been recommended that both the reburn fuel injector and burnout air injector windboxes be multicompartmented with individual control dampers on each compartment. This is because one large diameter jet and compartment provided for better deep furnace penetration and dispersion while smaller diameter angled jets and compartments provided for

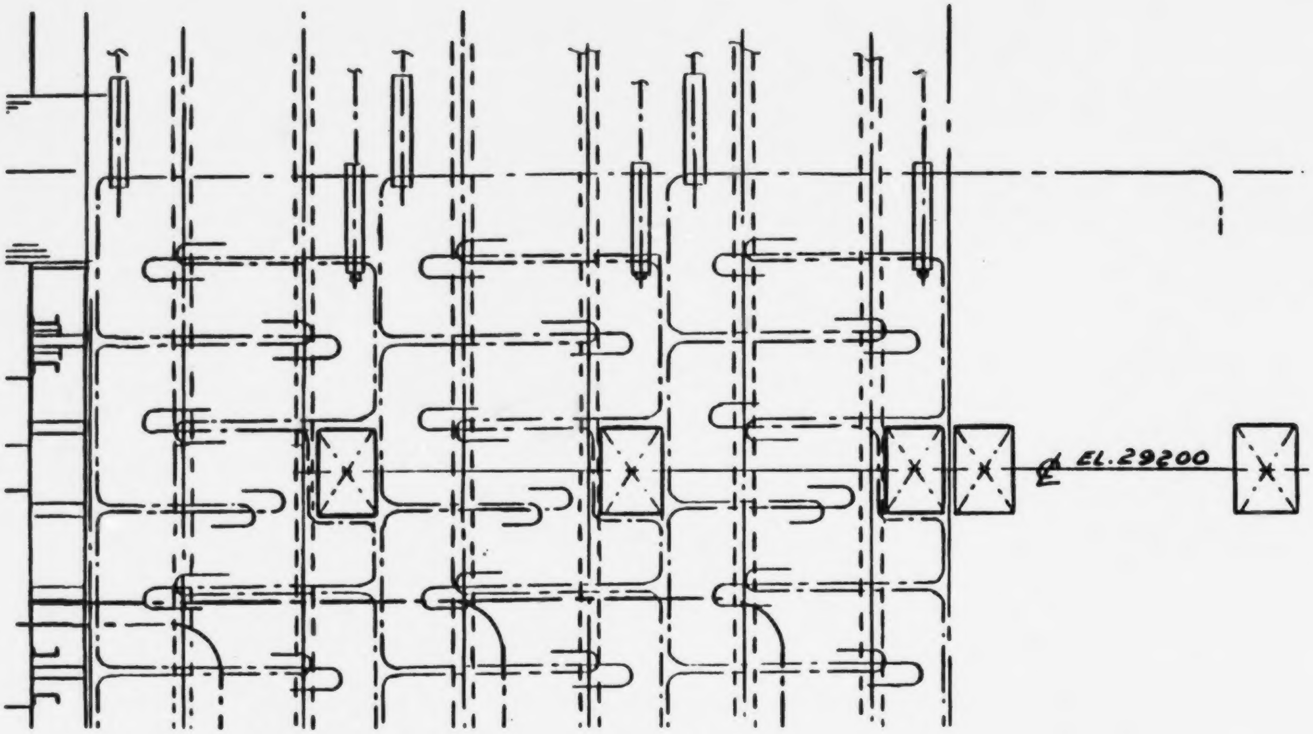


Figure 5-2. Example of Tube Modifications For Burnout Air Injector Installation

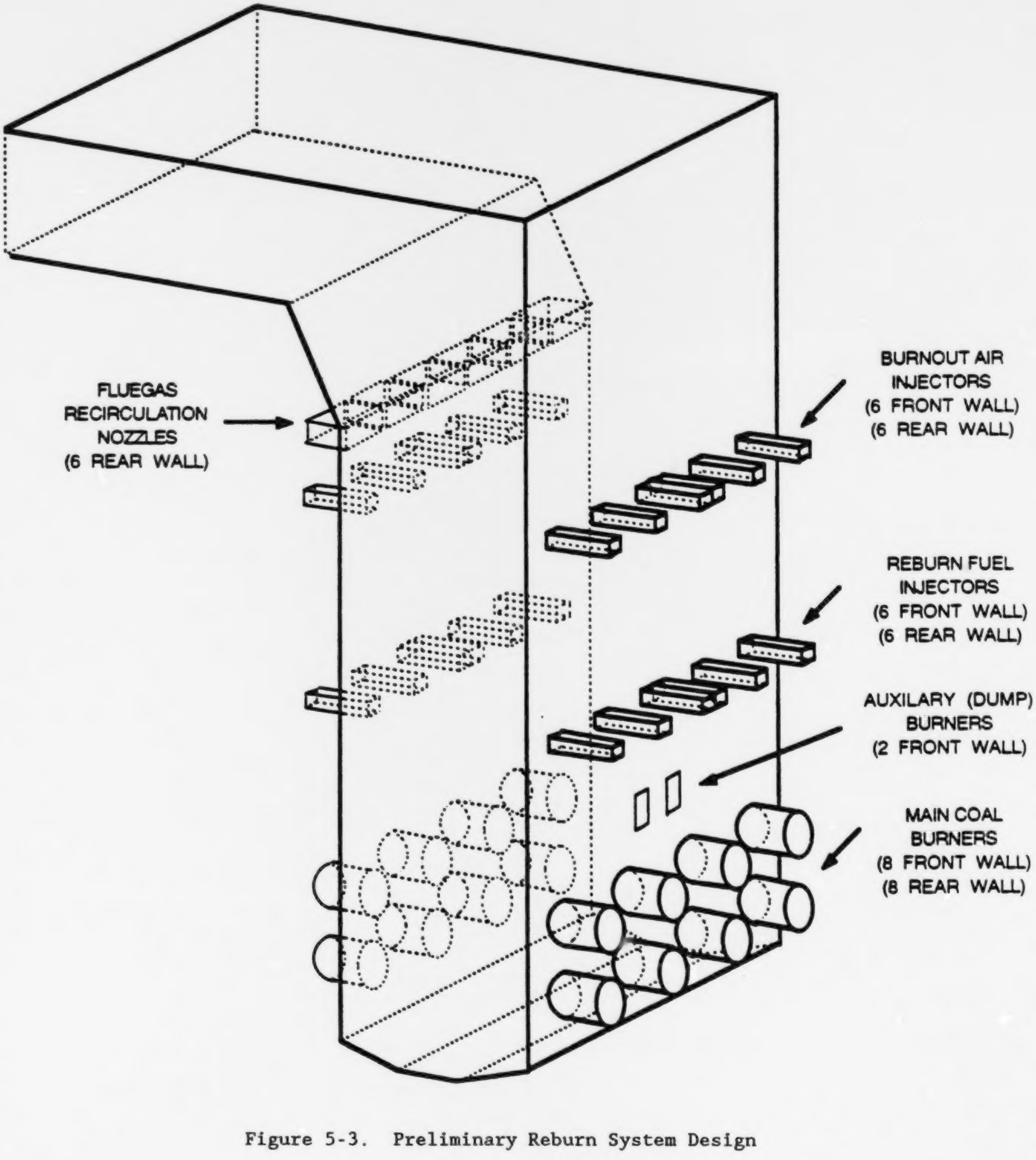

FLUEGAS
RECIRCULATION
NOZZLES
(6 REAR WALL)
BURNOUT AIR
INJECTORS
(6 FRONT WALL)
(6 REAR WALL)
REBURN FUEL
INJECTORS
(6 FRONT WALL)
(6 REAR WALL)
AUXILARY (DUMP)
BURNERS
(2 FRONT WALL)
MAIN COAL
BURNERS
(8 FRONT WALL)
(8 REAR WALL)

Figure 5-3. Preliminary Reburn System Design

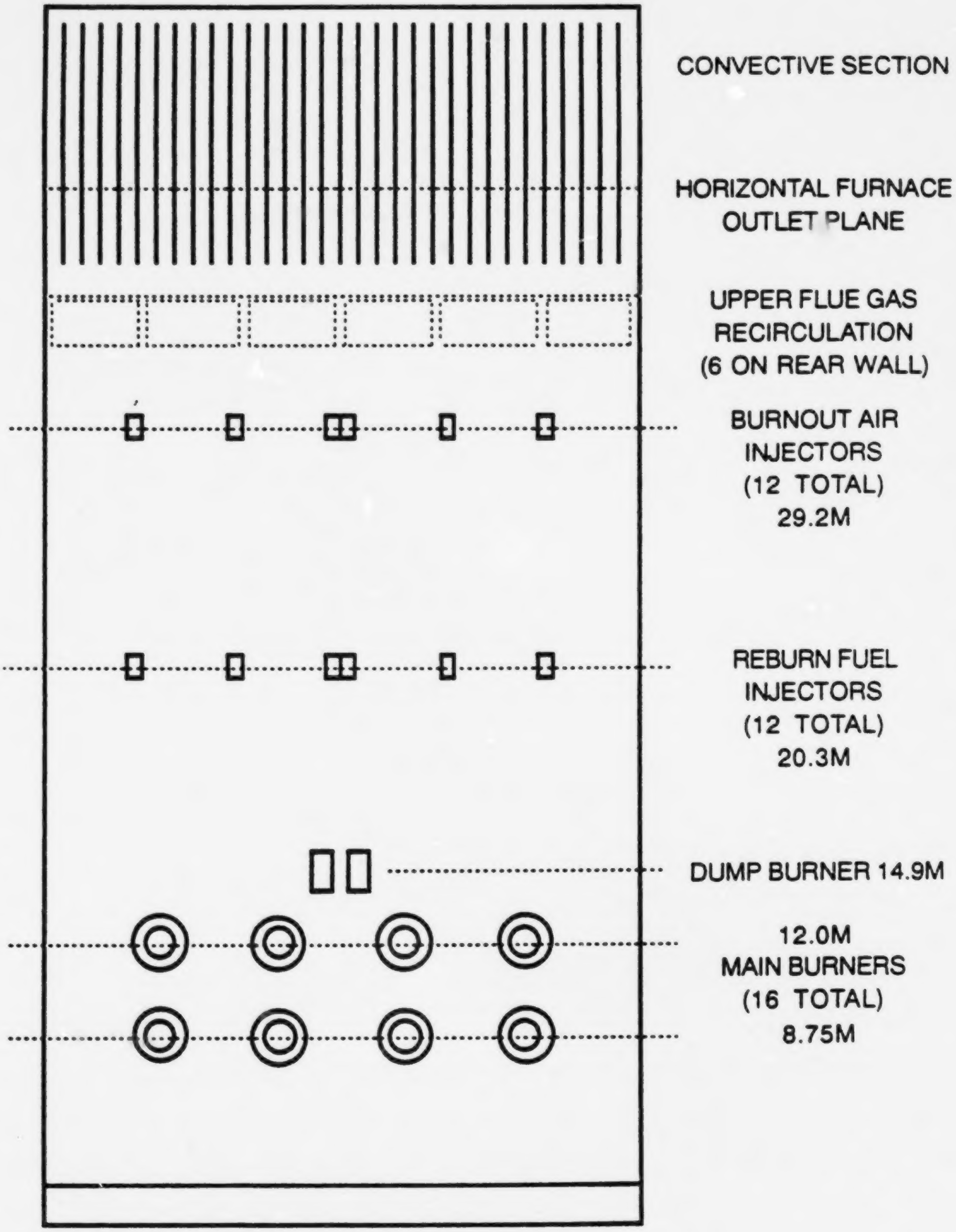

CONVECTIVE SECTION
HORIZONTAL FURNACE OUTLET PLANE
UPPER FLUE GAS RECIRCULATION (6 ON REAR WALL)
BURNOUT AIR INJECTORS (12 TOTAL) 29.2M
REBURN FUEL INJECTORS (12 TOTAL) 20.3M
DUMP BURNER 14.9M
12.0M
MAIN BURNERS (16 TOTAL)
8.75M

Figure 5-4. Preliminary Reburn System Design - Front Elevational View

better near field (jet) mixing and dispersion. The individual compartment control capability is recommended for performance optimization during initial system start-up and potentially for normal load following operation.

For the reburn fuel injector windboxes the design was based on 10% FGR for the reburn fuel transport media, 20% natural gas (percent of total fuel heat input) reburn fuel, and a nozzle exit jet velocity of 183 ft/sec (55m/s) although a jet velocity range 146 - 183 ft/s (45-55 m/s) appears acceptable. The high end of range jet velocity was selected such that fan and component capacity was sufficient. In addition, it may be possible and desirable, during field optimization, to decrease reburn FGR flowrate to further minimize the reburn system effect on furnace thermal performance. Thus, to accommodate the decreased jet velocity that would result from decreased FGR flow while still providing sufficient jet momentum for penetration and dispersion the higher design velocity was selected.

The general reburn windbox nozzle configuration is presented in Figures 5-5 and 5-6, and 5-7. Vertical tilt capability has been designed into the arrangement as overall penetration and dispersion were shown to be significantly altered with this feature in the flow model along with zone residence time control. Thus, the benefit in the Ladyzhinskaya boiler would be improved control and optimization of the reburn system performance while minimizing boiler operation impacts.

The lower compartment with the larger single jet nozzle incorporates yaw (horizontal) adjustment capacity to optimize the deep furnace penetration and dispersion. The upper compartment with the two smaller jet nozzles has fixed

- NUMBER OF REBURN FUEL WINDBOXES 12 TOTAL (6 FRONT/6 REAR WALL)

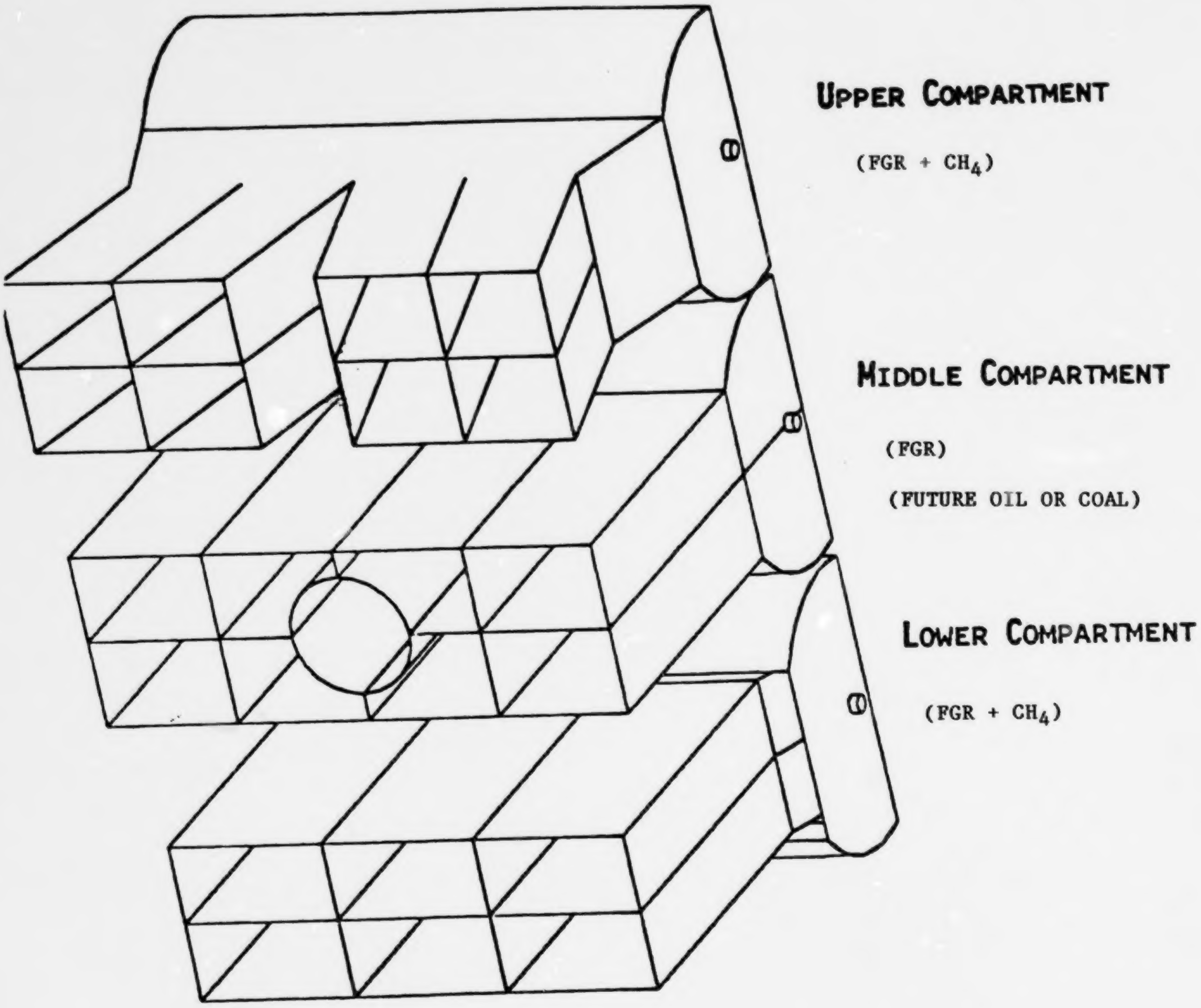
- LOCATION ELEV. 20.3 METERS

- WINDBOX CONFIGURATION
  - 3 COMPARTMENTS PER WINDBOX - NATURAL GAS/OIL (FUTURE COAL)/ NATURAL GAS
  - TOP NATURAL GAS 36^0 INCLUDED ANGLE "PANT LEGS" (18^0 IN POSITIONS #1, #3, #4, AND #6)
  - MIDDLE OIL/(FUTURE COAL) - CENTRALLY LOCATED OIL GUN (COAL NOZZLE)
  - BOTTOM NATURAL GAS $\pm$ 10^0 YAWABLE

- VERTICAL TILT (MANUAL) $\pm$ 30^0 FROM HORIZONTAL
- NOMINAL WINDBOX WIDTH .55 METERS (22 INCHES)
- NOMINAL WINDBOX HEIGHT .76 METERS (30 INCHES)
- DESIGN VELOCITY 55M/S (183 FT/SEC) (WITH NATURAL GAS COMPARTMENTS ONLY)

Figure 5-5. Reburn Fuel Injector Configuration

(FURNACE SIDE VIEW) (SIX INJECTORS EACH/FRONT-REAR WALLS)


UPPER COMPARTMENT
(FGR + CH_4)
MIDDLE COMPARTMENT
(FGR)
(FUTURE OIL OR COAL)
LOWER COMPARTMENT
(FGR + CH_4)

- ALL COMPARTMENTS TILT (COMMON LINKAGE)
- LOWER COMPARTMENT YAWS

Figure 5-6. Reburn Fuel Injector Windbox Arrangement

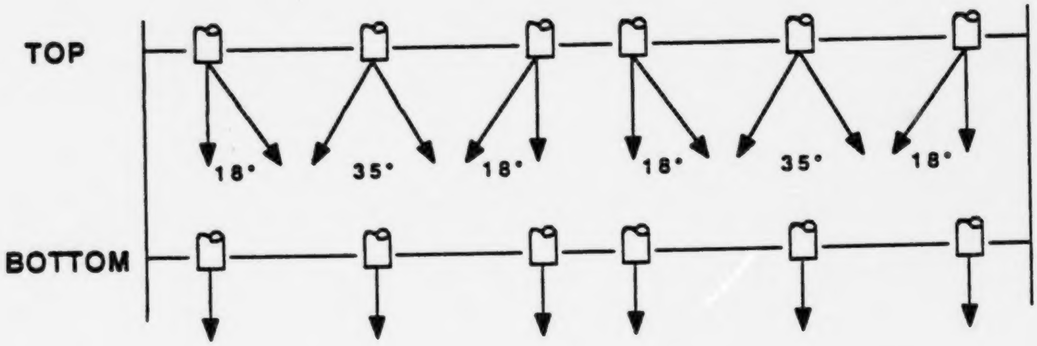

TOP
BOTTOM
18°
35°
18°
18°
35°
18°

Figure 5-7. Pant-leg Arrangement/Reburn Fuel Injectors

horizontal split arrangement to disperse well in the near jet field. A third, optional, centrally located compartment provides for future oil and/or coal reburn potential.

The reburn fuel (natural gas) would be premixed with the FGR at the nozzle exit with a natural gas spud located at the nozzle tilt axis centerline at the rear of the nozzle.

The burnout air windbox and compartment arrangement was similar. However, only two compartments were required and yaw adjustment capability has been added to the two smaller upper compartment nozzle tips. This configuration is presented in Figures 5-8 and 5-9.

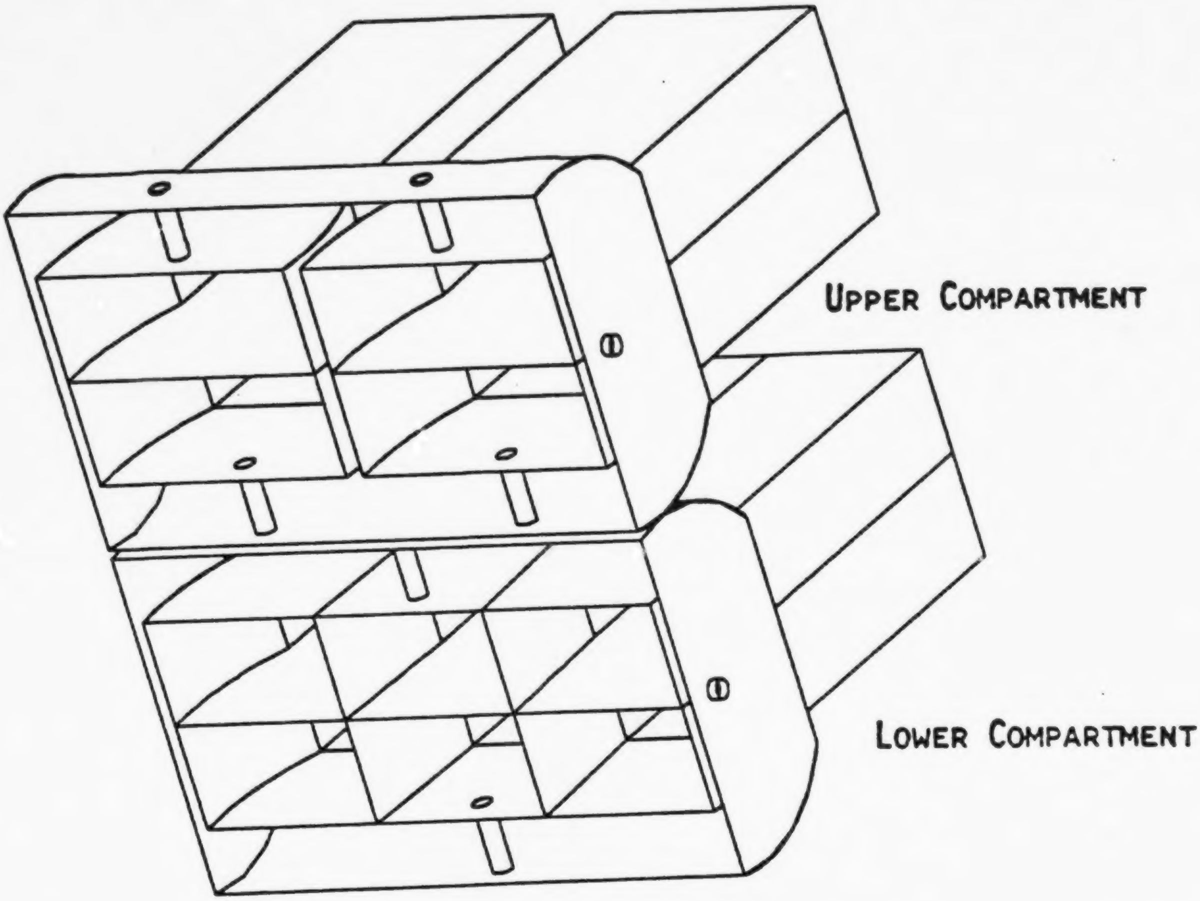
For the burnout air windboxes for the calculated burnout, air total flow of 525,829 lb/hr (238,579 Kg/hr) and a design velocity of 229 ft/S (70 m/s) was selected per the flow model results. [However, if an alternate flowrate is selected based on the supplementary recommendations, (Section 9) the velocity and design should be revised accordingly to maintain jet momentum.]

REBURN SYSTEM GENERAL ARRANGEMENT

The overall system configuration has met the reburn system design criteria and may be further optimized upon installation in the Ladyzhinskaya boiler. Furnace sectional views showing front, side, and elevational general arrangements with the reburn system in place have been developed and are included in Appendix A. Windbox arrangements showing the assemblies for both

o	Number of Windboxes	12 (6 front/6 rear)
o	Elevation	29.2 meters
o	Number of Compartments Per Windbox	2
o	Bottom compartment Configuration Single Nozzle $\pm$ 10^{0} yawable	
o	top compartment configuration Two yaw independent nozzles Left - 18^{0} -0^{0} yawable Right 0^{0} - 18^{0} yawable	
o	Vertical Tilt (manual) $\pm$ 30^{0} from horizontal	
o	Design Velocity	229 FPS
o	Nominal Windbox Width	0.46M (18 inches)
o	Nominal Windbox Height	0.61M (24 inches)

Figure 5-8. Burnout Air Configuration


(WINDBOX SIDE VIEW) (SIX INJECTORS EACH/FRONT-REAR WALLS)

UPPER COMPARTMENT
LOWER COMPARTMENT

- ALL COMPARTMENTS TILT (COMMON LINKAGE)
- UPPER COMPARTMENT NOZZLES HAVE INDEPENDENT YAW
- LOWER COMPARTMENT NOZZLE YAWS

Figure 5-9. Burnout Air Injector Windbox Arrangement

the reburn fuel and burnout air windboxes have also been developed and are also included in Appendix A. These drawings were also transmitted to the Soviet side in June, 1989.

SECTION 6

FURNACE THERMAL PERFORMANCE

INTRODUCTION

The objective of this task was to investigate the potential impact of retrofitting a reburn NO_x reduction system on furnace performance for the Ladyzhinskaya Power Station host boiler. Specific objectives were to determine if changes would occur and the magnitude, thereof, in: the furnace exit gas temperature, the furnace hopper gas temperature, and the distribution of and total heat absorption in the furnace with and without the reburn NO_x reduction system. These parameters were investigated for both natural gas and coal as the reburn fuel.

Other objectives were to estimate any changes in combustion efficiency and/or flyash carbon content when the reburn system was in operation. No assessment was made on convective pass performance (superheat, reheat or economizer sections) with the reburn system due to any changes in flue gas weights (mass flows), total boiler heat absorption (as compared to furnace heat absorption), or changes in boiler exit gas temperature (as compared to furnace exit gas temperatures) in this thermal performance analysis.

DESCRIPTION OF UNIT

The subject unit was a balanced draft, natural circulation, opposed wall fired, supercritical, coal fired boiler. At the rated capacity of 300 megawatts electrical the design superheated steam flow was 2,205,000 lb/hr (1,000 tons metric/hr) at conditions of 1013°F (545°C) and 3625 psig (255 Kg/cm^2). The single stage reheat steam flow at this load was 1,720,000 lb/hr (780 tons metric/hr) at conditions of 1013°F (545°C) and 555 psig (39 Kg/cm^2).

The indirect pulverized coal firing system consisted of two drum and ball type pulverizers feeding to a cyclone separator and silo coal storage system. The separated transport air and fuel fines were passed through a boost fan and split into individual burner lines. Each burner line was routed under the coal storage silo where it is mixed with the stored coal and subsequently fed to the burners. Each of the two pulverizer and silo storage systems was linked to one elevation of eight (8) burners. There were two fuel elevations totaling 16 burners in the boiler. Each elevation of 8 burners is arranged with 4 burners on the front wall and 4 burners on the rear wall. Preheated secondary air from the two regenerative air heaters was individually ducted to each burner. The transport air and coal stream entered the burners through perpendicular inlets at the burner front and was passed unswirled into the furnace. The secondary air was swirled in the burners before entering the furnace. Four of the eight burners on each wall were swirled clockwise (viewed from the back of the burner into the furnace). On the front wall this included the right two burners on the top elevation and the two outside burners on the lower elevation. The two inside burners on the lower elevation and left two burners on the top elevation were swirled counter-clockwise. On the rear wall this pattern was reversed.

There were also two "Dump Burners" injecting a portion of the separated pulverizer transport air and fuel fines on the front wall, centered and above the top main burner elevation.

Recirculated flue gas was used in the boiler both to control pulverizer outlet temperature and boiler steam temperature. Approximately 4% of the total 18% recirculated flue gas (FGR) was used for pulverizer temperature control and the remaining 14% was injected into the furnace from the rear wall through six ports located near the furnace outlet.

FURNACE THERMAL PERFORMANCE ANALYSIS METHODOLOGY

The furnace thermal performance analysis was completed utilizing a proprietary Combustion Engineering developed computer code (Figure 6-1). The function of the program was to determine, through a series of heat balance calculations, the heat transfer from the combustion products to the waterwalls, the corresponding gas temperatures, and the furnace outlet temperature of the combustion products. The combustion history and combustion products were determined based on a fuel analysis, fuel and air mass flow rates and injection locations and for solid fuels the particle size distribution and a set of fuel char combustion kinetics.

The computer program was first set up to emulate the current as found or baseline conditioning using the furnace physical, fuel, fuel size and operating characteristics provided by the Soviet side (Figure 6-2). As no fuel sample was available for analysis the coal char kinetics from a similar coal existing in a Combustion Engineering database were used (Table 6-1). The

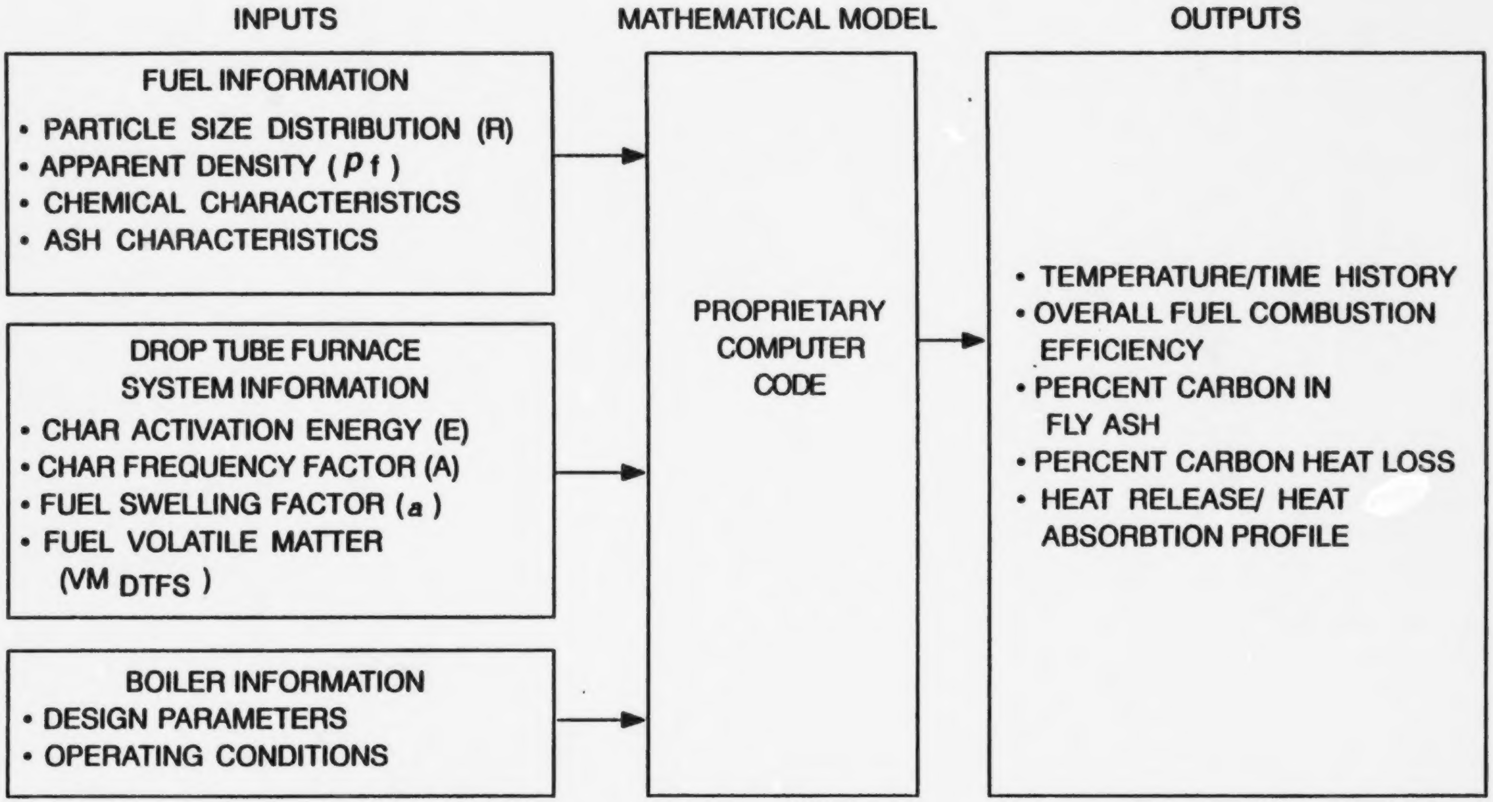
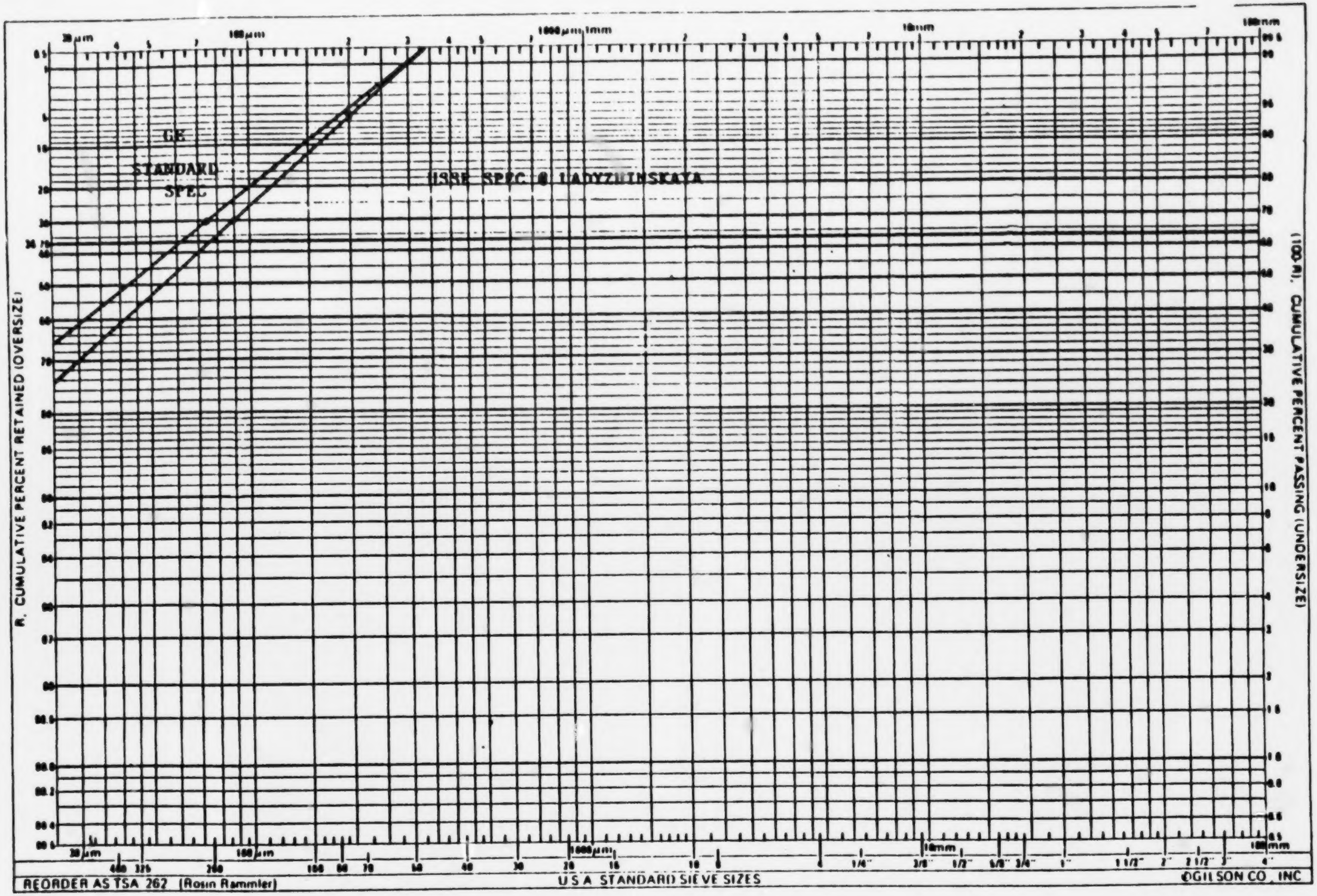

INPUTS
MATHEMATICAL MODEL
OUTPUTS
FUEL INFORMATION
• PARTICLE SIZE DISTRIBUTION (R)
• APPARENT DENSITY (ρf)
• CHEMICAL CHARACTERISTICS
• ASH CHARACTERISTICS
DROP TUBE FURNACE SYSTEM INFORMATION
• CHAR ACTIVATION ENERGY (E)
• CHAR FREQUENCY FACTOR (A)
• FUEL SWELLING FACTOR (a)
• FUEL VOLATILE MATTER (VM DTFS)
BOILER INFORMATION
• DESIGN PARAMETERS
• OPERATING CONDITIONS
PROPRIETARY COMPUTER CODE
• TEMPERATURE/TIME HISTORY
• OVERALL FUEL COMBUSTION EFFICIENCY
• PERCENT CARBON IN FLY ASH
• PERCENT CARBON HEAT LOSS
• HEAT RELEASE/ HEAT ABSORBTION PROFILE

Figure 6-1. Flow Diagram For Boiler Combustion Performance Model Simulation



$R = 100e^{-\left(\frac{x}{\bar{x}}\right)^n}$

Log Log R = $-n$ log x + K

Where X = Particle Size

$\bar{x}$, Absolute Size Constant = ______________
(at 36.79%)

n, Distribution Coefficient = ______________
(slope)

USSR - 63% thru 200 mesh

99% thru 50 mesh

CE - 70% thru 200 mesh

99% thru 50 mesh

Figure 6-2. Rosin-Rammler Screen/Sieve Analysis Chart

Table 6-1. Furnace Combustion Performance Model Simulation Inputs/Fuel Information

	SOVIET COAL		US DATA BASE COAL	
	AS RECEIVED	DRY ASH FREE	AS RECEIVED	DRY ASH FREE
PROXIMATE ANALYSIS				
MOISTURE	12.0	-	19.8	-
VOLITILE MATTER	22.2	42.0	29.0	41.0
FIXED CARBON	30.6	58.0	41.8	59.0
ASH	35.2	-	9.4	-
	100	100	100	100
ULTIMATE ANALYSIS				
MOISTURE	12.0	-	19.8	-
HYDROGEN	3.0	5.7	3.6	5.1
CARBON	40.1	76.0	53.1	75.0
SULPHUR	2.0	3.8	0.7	1.0
NITROGEN	0.8	1.5	1.4	2.0
OXYGEN	6.9	13.0	12.0	16.9
ASH	35.2	-	9.4	-
	100	100	100	100

CHAR KINETICS

SWELLING FACTOR	1.0
CHAR DENSITY	0.53 g/cm^3
CHAR SURFACE AREA	72 m^2 /g
CHAR FREQUENCY FACTOR	36.8 g/cm ^{2} sec in O_2 atm.
CHAR ACTIVATION ENERGY	20,900 cal/mole

COAL PARTICLE SIZE DISTRIBUTION

GIVEN

program was then calibrated for this unit based on a furnace gas temperature profile provided by the Soviets.

The furnace thermal performance with reburning was then determined using the design locations and flow rates for the reburn fuel, reburn nozzle recirculated flue gas, and burnout air and the revised main burner fuel and air flows and the upper furnace flue gas recirculation flow (Table 6-2). Both coal and natural gas were examined as potential reburn fuels.

RESULTS OF ANALYSIS

Furnace Gas Temperature Profile:

As stated above the first step in this analysis was to set up the computer program to emulate the Soviet provided or given furnace gas temperature profile. These results are presented in Figure 6-3. By varying the conductivity of the furnace waterwalls the computer predicted "as found" furnace gas temperature profile was matched to the Soviet provided "given" gas temperature profile (see report Section 2) to within 250°F (140°C).

The peak furnace gas temperature predicted by the program of approximately 2750°F (1510°C) agreed well with the peak temperature provided by the Soviets. (Note that the furnace gas temperatures presented represent the average gas temperature for a cross section of the furnace at a given elevation. No information was provided nor was any attempt made to assess the gas temperature contour across a given furnace cross section.) The program predicted that the peak gas temperature would occur at approximately

Table 6-2. Furnace Combustion Performance Model Simulation Inputs/Boiler Information

- **FURNACE GEOMETRY**

DEPTH: 8.66m (28.4 ft)
WIDTH: 1/2 x 17.32m (56.8/2 = 28.4 ft)
HEIGHT (EFFECTIVE): 33.28m (109.2 ft)

- **INJECTOR ELEVATION**

BURNERS BOTTOM ROW	: 8.75m	(28.7 ft)
BURNERS TOP ROW	: 12.00m	(39.4 ft)
DUMP	: 14.90m	(48.9 ft)
UPPER FUEL	: 20.30m	(66.6 ft)
BURNOUT AIR	: 29.20m	(95.8 ft)
UPPER GAS RECIRCULATION:	35.10m	(115.2 ft)

- **MASS FLOWS**

50% OF GIVEN FUEL, AIR AND GAS RECIRCULATION

NOTE: Only one-half of the furnace was modelled because the computer code was developed and calibrated on more "square" furnaces (width by depth). This "partial furnace modelling" has been done regularly in the past by Combustion Engineering, Inc. to analyze divided furnace arrangements.

Effective height deducts the furnace volume lost with the hopper slopes.

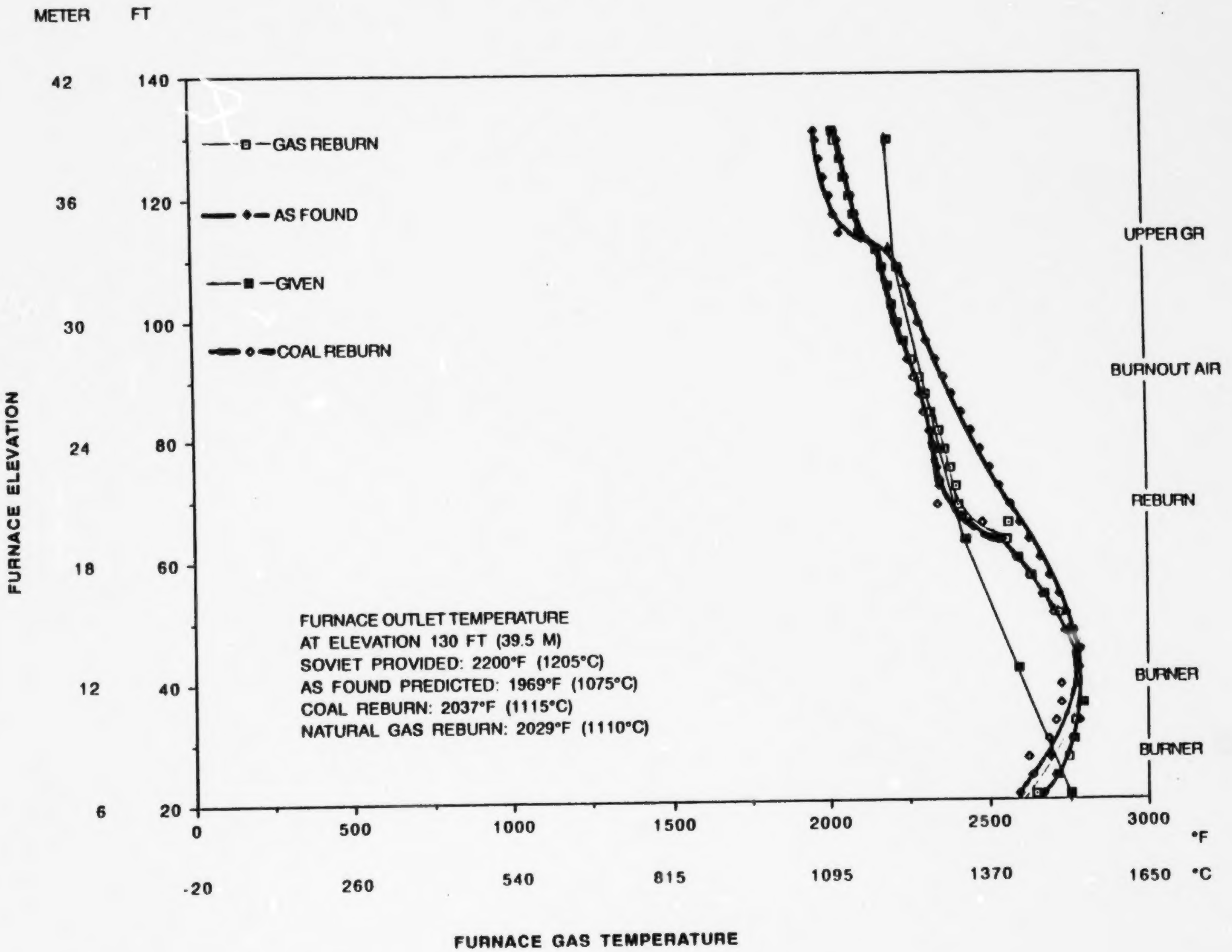


Figure 6-3. Predicted Furnace Gas Temperature Profile

the top main burner elevation of the furnace, whereas, for the gas temperature profile provided by the Soviets the peak gas temperature occurred near the furnace hopper elevation.

Accounting for this difference in location for the peak flame temperature the remainder of the predicted furnace gas temperature profile agrees well with the provided information. The predicted current as found furnace exit gas temperature at 1970°F (1075°C) was approximately 230°F (130°C) lower than the temperature provided by the Soviets. This difference in temperature is principally due to the quenching effect of the upper furnace flue gas recirculation (FGR). Note that the upper furnace FGR was a recent retrofit to the Ladyzhinskaya boiler and may or may not be accounted for in the Soviet provided gas temperature data. In addition, the recently retrofit upper furnace flue gas recirculation nozzles may have insufficient jet momentum (velocity) to mix well with the upper furnace main flue gas products. This would result in a stratified flue gas profile at the furnace exit. The computer program used for the analysis does not account for stratification and assumes a well mixed planar average profile.

For reburning, 20% of the total fuel heat input was shifted evenly from the two (2) main burner elevations to the reburn elevation. Also, the reburn system design utilized 10% FGR with the reburn fuel. This reburn system FGR was diverted from the upper furnace FGR such that the total furnace FGR remained constant. For this analysis the main burner zone stoichiometry was maintained as well as the total furnace stoichiometry. Both coal and natural gas were examined as prospective reburn fuels. The predicted furnace gas temperature profile was very similar for both of the reburn fuels.

The predicted furnace gas temperature profile with reburning (three stage combustion) has been presented in Figure 6-3. The predicted current or "as found" gas temperature profile has also been shown for comparison.

As can be seen the overall furnace gas temperature profile with reburning was predicted to be similar to the current as found temperature profile. Small changes in furnace gas temperature due to reburning have been predicted for several elevations of the furnace. The furnace bottom or hopper region gas temperature was anticipated to be approximately 50°F to 100°F (28°C to 56°C) lower with reburning. This was due to the decreased firing rate or loading of the main burner elevations. It is anticipated that with reburning the lower furnace operations (gas temperature, heat absorption, slag tapping, etc.) will be similar to current normal boiler operations at 80% boiler load. The magnitude and location of the peak furnace gas temperature have been predicted to remain unchanged with reburning at 2750°F (1510°C) and slightly above the main burner elevation, respectively. The gas temperature quench rate between the main burner elevation and the reburn elevation is slightly greater with reburning due to the decreased main burner firing rate. At the reburn fuel inlet elevation there is an initial significant decrease in gas temperature due to the 10% flue gas recirculation injected with the reburn fuel. After this initial temperature drop the furnace gas, temperature quench rate was decreased due to the chemical reduction reactions of the reburn fuel. For this section of the furnace the gas temperature quench rate is predicted to also be less than the current as found quench rate. This low quench rate continues through the burnout zone as the combustion process is completed. At the upper furnace flue gas recirculation elevation the gas temperature drops slightly due to the quenching effect of the remaining FGR.

The temperature drop at this elevation with reburning is predicted to be only 50°F (27°C) compared to the 160°F (88°C) drop with the current "as found" configuration. This is consistent with the decrease in upper furnace FGR quantity from approximately 14 percent with the "as found "configuration to approximately 4 percent with the reburn system. The furnace exit gas temperature with reburning was predicted to be approximately 2030°F (1110°C) or approximately 60°F to 70°F (35°C to 40°C) higher than the current as found configuration.

Furnace Waterwall Heat Absorption Profile:

The waterwall heat absorption rate profile mimics the furnace gas temperature profile (Figure 6-4). This is readily explained by the fact that greater than 90 percent of the heat absorption in a furnace is due to radiation heat transfer and radiation heat transfer is fourth power dependent on temperature (T^4).

The predicted waterwall heat absorption rate profile for the current "as found" condition as well as for the two reburn cases was maximized at or slightly above the top main burner elevation. The predicted maximum heat absorption rate for the three cases examined was nearly identical at approximately 73,000 Btu/hr-ft^2 (198,000 KCal/hr*M^2).

For the furnace elevations between the top main burner (40 ft or 12.2 meter) and the upper gas recirculation injectors (115.2 ft or 35.1 meter) the predicted waterwall heat absorption rates were lower for the two reburning cases than for the "as found" case. Above the upper gas recirculation

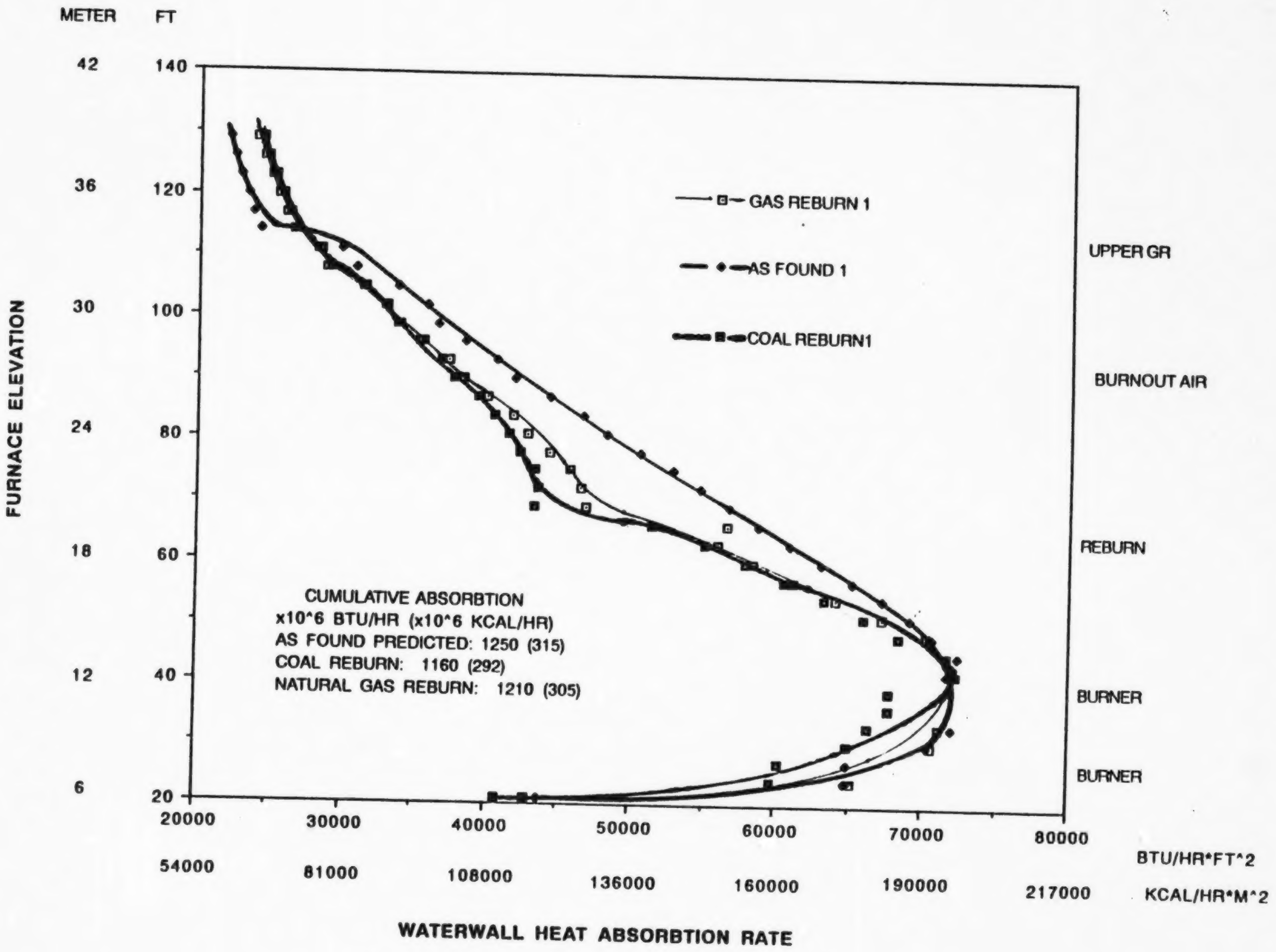


Figure 6-4. Waterwall Heat Absorbtion Profile

injectors the waterwall heat absorption rates are predicted to be approximately 15% higher with reburn compared to the "as found" rates.

Based on the above predicted absorption rates the following statements can be made. First, the cumulative waterwall heat absorption will decrease with reburning. (cumulative waterwall heat absorbtion is determined by integrating the heat absorption rates over the furnace height or determining the area under the heat absorption rate versus furnace height profile.) With coal reburning the cumulative absorption was predicted to decrease by about 8 percent to 1160 x 10^6 Btu/hr (292 x 10^6 Kcal/hr) with coal reburning versus 1250 x 10^6 Btu/hr (315 x 10^6 Kcal/hr) as found. With natural gas reburning the cumulative waterwall absorption was predicted to decrease by about 4 percent to 1210 x 10^6 Btu/hr (305 x 10^6 Kcal/hr) with natural gas reburning versus 1250 x 10^6 Btu/hr (315 x 10^6 Kcal/hr) as found).

Additionally, for this supercritical boiler where the fluid temperature (and thus metal temperature) is changing over the furnace height (versus constant fluid temperature with changing steam quality for a subcritical boiler) waterwall fluid and metal temperatures are predicted to be similar or lower with reburning. This can be seen by observing that the cumulative heat absorption at any given elevation are similar or lower with reburning.

However, it would be prudent to examine for changes in the heat duty (or sectional absorptions) in the remaining boiler heat transfer surfaces (superheat, reheat and economizer). Slight increases in absorption rates for these sections are anticipated due to the predicted furnace exit gas temperature increase with reburning. In particular, the upper furnace (from upper gas recirculation injector elevation to outlet header) waterwall metal temperature should be examined if the anticipated increase in economizer duty (absorption) compensates for the predicted decreased waterwall absorption. (Note that a total compensation in heat absorption between the waterwalls and the economizer is not probable because it would mean that no changes could occur in the intervening superheat and reheat surfaces. However, any change in economizer absorption would subsequently result in a shift in the waterwall fluid/metal inlet temperature and overall profile.) A total boiler and complete sectional heat balance analysis was beyond the scope of this program.

The computer based analyses also predicted slight changes in the boiler carbon heat loss/carbon content in the flyash with reburning. For natural gas reburning the carbon heat loss was anticipated to decrease with the flyash carbon context predicted to lower from 2.3% "as found" to 0.6% with natural gas reburn. (Note that the "as found" predicted flyash carbon content of 2.3% agrees well with Soviet provided 1.0% flyash carbon data. This tends to confirm the similarity of the Soviet coal with the database coal used in the analyses.) For coal reburning the carbon heat loss was anticipated to increase with the flyash carbon content predicted to increase slightly from 2.3% "as found" to 3.5% with reburning. And finally, although not quantified, it was anticipated that the overall boiler efficiency would decrease with natural gas fuel hydrogen content and subsequent increased flue gas moisture latent heat loss (Table 6-3).

Table 6-3. Boiler Thermal Performance Summary

- FURNACE HEAT ABSORBTION WILL BE UP TO 8% LESS WITH COAL REBURN AND 4% LESS WITH NATURAL GAS REBURN

- FURNACE EXIT GAS TEMPERATURE WILL BE UP TO 70^{O}F (40^{O}C) HIGHER WITH COAL REBURN AND 60^{O}F (35^{O}C) HIGHER WITH NATURAL GAS REBURN

- FURNACE BOTTOM GAS TEMPERATURE WILL BE UP TO 80^{O}F (45^{O}C) LOWER WITH REBURN

- OVERALL FURNACE WATERWALL HEAT ABSORBTION PROFILES WILL NOT BE SIGNIFICANTLY ALTERED WITH REBURNING

- CARBON HEAT LOSS WILL DECREASE WITH NATURAL GAS REBURN
  CARBON-IN-FLYASH: 2.3% BASELINE 0.6% NATURAL GAS REBURN

- CARBON HEAT LOSS WILL INCREASE WITH COAL REBURN
  CARBON-IN-FLYASH: 2.3% BASELINE 3.5% COAL REBURN

- OVERALL BOILER EFFICIENCY WILL BE UP TO 1.0% LESS WITH NATURAL GAS REBURN DUE TO INCREASED MOISTURE FROM FUEL LOSSES

SECTION 7

GENERAL REBURN CONTROL SYSTEM PHILOSOPHY

For completeness we have presented a general operating philosophy for integrating the reburn system into the normal boiler operation. A detailed reburn control system logic diagram would have required additional information on the existing boiler control system and operating philosophy and was beyond the scope of this project.

In general, the control system envisioned for reburn NO_x control at the Ladyzhinskaya boiler will be load based. The reburn system would not be placed into service until the boiler load was sufficient to achieve stable burner/boiler operation with the main burners in service only. Upon further boiler load increases the reburn system would be ramped into full service. Upon achieving full in service operation with the reburn system further boiler load increases up to full boiler load would be achieved by distributing the fuel demand between the main burners and the reburn fuel injectors to maintain a constant reburn fuel: main burner fuel ratio. This type of operation would yield a constant reburn zone stoichiometry for optimal NO_x control over the boiler load range; provide a smooth transition into and out of reburn operation; and not affect boiler start-up.

The burnout air system would be linked to the reburn fuel flow to maintain constant burnout zone stoichiometry.

The reburn injector flue gas recirculation (FGR) flow rate would be maintained at a constant ratio to boiler load to maintain mixing between the reburn injector flows and the main burner combustion products.

The reburn fuel injector FGR system would be set to operate independently of the reburn fuel system to minimize furnace gas and steam temperature oscillations.

Safety interlocks with the main burner, boiler and turbine systems would be provided to either prevent start-up, operation or trip the reburn fuel system at appropriate times. Additional safety interlocks would be provided to limit reburn fuel usage until the remaining reburn system (including burnout air system) components were proven to be operating normally. Conversely, the reburn fuel would be tripped out of service if any other system component operated abnormally.

Finally, and importantly, both the reburn system hardware design and control system would have inherent flexibility with bias controls and hardware adjustability to optimize the reburn system operation in the boiler.

SECTION 8

ALTERNATE REBURN FUELS

The use of either oil or coal as a reburn fuel in lieu of natural gas was examined at the request of the Soviet side. This examination was requested for two reasons. First, oil (heavy oil in particular) and coal are less costly than the natural gas. Second, during some winter months the use of natural gas as a utility boiler fuel may be limited due to district heating requirements in the Vinnitsa area.

The use of natural gas as the reburn fuel had initially been selected based on fuel selection criteria contained in the literature.[1] In particular, the literature has shown that:

- Reburn fuels with a high H/C ratio were effective due to their increased propensity for forming OH and H radicals.
- Reburn fuels should be highly reactive due to their relatively short residence time in the reburn zone.
- Reburn fuels should have a low nitrogen content to prevent and/or minimize additional formation of NO_x.

Clearly, natural gas meets these criteria better than most oils or coal. However, it may be possible to use oil or coal as a reburn fuel with the understanding that there may be performance implications in terms of NO_x reduction capabilities, combustion efficiency and other boiler side impacts. On reexamination of the advantages and disadvantages of using an alternative reburn fuel it was determined that for this program it would be prudent to select natural gas as the primary design reburn fuel.

The design can be modified to enable use of oil or coal as a reburn fuel at a future date as the technology of reburning matures and some of the fundamental questions on fuel type have been answered.

Tables 8-1 and 8-2 identify significant items which should be taken into account when and/or if oil or coal is used an alternative to natural gas for reburning.

Table 8-1. Oil As Reburn Fuel

- Chemical Reduction Reactions Similar to Natural Gas
- Oil Atomization
    - Steam Dual Fluid
    - Small Droplet Size
- High Grade Oil (low asphaltine content; high H/C ratio) Viewed as better fuel from atomization, combustion efficiency, and reburn effectiveness standpoint
- Low nitrogen content preferred to limit NO_X formation

Table 8-2. Coal As Reburn Fuel

o Chemical Reduction Reactions Similar to Natural Gas

o Not As Effective Due To Low H/C Ratio
(Requires More Reburn Fuel and/or Longer Reburn Zone)

o Fine Particle Size Required (No oversized material)
For High Combustion Efficiency and Greater Reaction
During Reburning

o Low Nitrogen Content Recommended
To Limit NO_X Formation

o High Fuel Reactivity (High Volatile Subbituminous)
Recommended
  - High Volatile
  - High Char Kinetics

o Soviet Coal (from proximate/ultimate analysis)
appears to be highly reactive, more definitive tests
necessary

SECTION 9

SUPPLEMENTARY FURNACE PERFORMANCE

ANALYSES AND RECOMMENDATIONS

INTRODUCTION

The reburn system as designed and modeled was predicted to increase the furnace exit gas temperature (FEGT) by approximately 60°F (35°C) with natural gas reburning and approximately 70°F (40°C) with coal reburning. These results were presented to the Soviet representatives at the preliminary design review meeting conducted in June, 1989.

Based on these predictions, the Soviets requested that additional furnace performance analyses be conducted in an attempt to decrease or eliminate this FEGT increase. It was also requested that an analysis be conducted on the effect of the upper furnace flue gas recirculation nozzles on FEGT with the goal of eliminating these additional waterwall penetrations. The Soviet representatives also stated that for the supplemental analysis and for the later detailed design if it is advantageous it may be possible to alter the burner (first stage) zone excess air level. For the preliminary reburn system design the burner zone excess air level was maintained constant both with and without reburning to minimize potential effects on ash slag tapping.

DESCRIPTION OF ANALYSES

Thus, the overall objective of the supplementary furnace performance analyses was to establish an optimized preliminary reburn system design in terms of furnace performance criteria while still meeting the design criteria for NO_x reduction established earlier.

In particular, the following the furnace performance criteria goals were desired:

1. Predicted Furnace Exit Gas Temperature (FEGT) for reburning which was equal to or below the predicted current non-reburn FEGT.
2. Predicted Furnace Waterwall Absorption for reburning which was equal to or above the predicted current waterwall absorption.
3. Eliminate the upper furnace FGR ports from the reburn system design even though they existed in the current non-reburn operation.
4. Maintain the fly ash carbon content while reburning to a level similar to the current non-reburn operation.

Based upon the above stated goals a sensitivity analysis was conducted to assess changes in 1) furnace exit gas temperature 2) cumulative furnace heat absorption and 3) flyash carbon content with permutations in A) total flue gas recirculation (FGR) flowrate, B) upper furnace FGR flowrate, C) main burner zone excess air (stoichiometry), D) reburn nozzle/zone FGR, and E) reburn fuel ratio.

The computer based analysis technique described in the previous Furnace Thermal Performance Analysis section was also utilized for the sensitivity study.

The sensitivity analysis was limited to the use of natural gas as the reburn fuel. The range of analysis (See Table 9-1) for any one of the variables examined during the sensitivity study was kept relatively small. This was done both to maintain the validity of physical flow modeling and to maintain confidence in the performance predictions.

SENSITIVITY STUDY RESULTS

Tables 9-2 and 9-3 present summaries of the predicted key performance results determined during the sensitivity study. Table 9-2 shows how each of the furnace performance criteria (FEGT, Absorption, Carbon in Fly Ash) were predicted to be effected upon changing each of the six (6) sensitivity study parameters individually.

On Table 9-2 it can be seen that decreasing the main burner exces air was predicted to be beneficial in meeting the sensitivity study objectives of decreasing (lowering) the furnace exit gas temperature and increasing (raising) the waterwall absorption. A slight increase was predicted for the fly ash, carbon content. Thus, it is recommended that for optimized reburning the main burner excess air level be decreased to the extent possible while still maintaining conditions appropriate for slag removal.

Table 9-1. Sensitivity Analysis Parameter Range

	CURRENT OPERATION	CURRENT REBURN SYSTEM DESIGN	SENSITIVITY STUDY RANGE
Main Burner Excess Air	20%	20%	5% - 20%
Total Flue Gas Recirculation	18%	18%	14.8% - 21%
Upper Furnace FGR	13.2%	3.2%	0% - 8.7%
Reburn FGR	N.A.	10%	7.5% - 10%
Reburn Fuel Ratio	N.A.	20%	12% - 20%

N.A. - Not Applicable

Table 9-2. Furnace Performance Sensitivity Analyses
Ladyzhinskaya Power Station
Summary of Results

PARAMETER CHANGED	FURNACE EXIT GAS TEMPERATURE	FURNACE WATERWALL ABSORPTION	CARBON IN FLYASH
Decreasing main burner excess air 20% to 5%	Lowered 20°F	Raised 6×10^6 Btu/hr	Raises 0.4%
Changing upper FGR elevation (35.1m) to reburn elevation (20.3m)	Raised 13°F	Lowered 8×10^6 Btu/hr	Raises 0.1%
Decreasing total FGR by 3.2% Via eliminating upper FGR	Raised 29°F	Raised 2×10^6 Btu/hr	No effect
Decreasing reburn FGR by 2.5% via increasing upper furnace FGR	Lowered 10°F	Raised 6×10^6 Btu/hr	No effect
Increasing total FGR by 3% via increasing upper FGR	Lowered 20°F	Lowered 2×10^6 Btu/hr	No effect
Decreasing total reburn fuel by 8% with main burner excess air @ 5%	Lowered 21°F	Raised 9×10^6 Btu/hr	No effect

To convert change in °F to °C multiply by 5/9

To convert Btu/hr to Kcal/hr multiply by 0.252

To convert meters to feet multiply by 3.28

Table 9-3. Furnace Performance Summary
Reburn Sensitivity Study
Ladyzhinskaya Power Station
Vinnitsa, U.S.S.R.

SENSITIVITY STUDY CASE		BASELINE AS FOUND	PRELIMINARY OPTIMUM RUBURN	REBURN CASE 1
Reburn Fuel Ratio	%	N.A.	20	12
Total Excess Air	%	20	20	28
Burner Zone Excess Air	%	20	20	5
Total FGR	%	18	18	21
Reburn FGR	%	N.A.	10	7.5
Upper Furnace FGR	%	13.2	3.2	8.7
Furnace Exit Gas Temperature	°F (°C)	1967(1075)	2028(1109)	1949(1065)
Furnace Heat Absorption $\times 10^6$ Btu/hr($\times 10^6$ Kcal/hr)		626(158)	606(153)	625(157)
Flyash Carbon Content	%	2.3	0.6	1.2

The two parameters analyzed pertaining to the objective of eliminating the upper furnace FGR ports both showed that this elimination would not be beneficial in regard to furnace performance. Eliminating the upper furnace FGR ports via maintaining the FGR mass flow but changing its location to the reburn elevation, second parameter on Table 9-2, resulted in a predicted increase in FEGT of 13°F (7°C) and lower waterwall absorption of $8x10^6$ Btu/hr ($2x10^6$ Kcal/hr). Eliminating the upper furnace FGR ports via decreasing the FGR flowrate resulted in a predicted increase in FEGT of 29°F (16°C). Therefore, it is recommended that the upper furnace FGR ports not be eliminated as part of the reburn system design.

The sensitivity analyses also examined the possibility of decreasing the amount of FGR used with the reburn fuel injectors by 2.5% from 10% to 7.5%. For the sensitivity study this decrease in reburn FGR was accomplished with an equivalent increase in upper furnace FGR. From a furnace performance standpoint this change was predicted to be beneficial with a predicted decrease in FEGT and an increase in waterwall absorption. However, even though this decrease in reburn FGR represents a small change it represents perhaps the most important deviation from the preliminary design and physical flow modeling. Therefore, while this decrease in reburn FGR is recommended the implications on reburn fuel penetration, mixing and dispersion should be reexamined during the detailed design phase.

Observing that decreasing or eliminating the upper furnace FGR ports was not beneficial, the next parameter studied the affect of increasing the amount of upper furnace FGR. The results predicted that this would be beneficial for lowering the furnace exit gas temperature although a slight lowering of the waterwall heat absorption was also predicted. Thus, it is recommended that the upper furnace FGR flowrate be increased for the optimized reburn system design.

Finally, the sensitivity study examined the possibility of decreasing the total reburn fuel flowrate. This was done with the assumption that the previously recommended decrease in main burner excess air will be incorporated into the optimized reburn system design. This assumption was necessary to maintain the reburn zone stoichiometry in the desired range for NO_x reduction.

Decreasing the reburn fuel ratio was beneficial with respect to both lowering the FEGT and raising the waterwall absorption. Thus, it is recommended that the reburn fuel flowrate be decreased for the optimized reburn system design.

Table 9-3 summarizes the process flows and the predicted furnace performance results for:

1. Baseline As Found Operation
2. Preliminary Reburn Operation
3. Optimized Preliminary Reburn Operation

As shown in the Table, with the optimized preliminary reburn design conditions the predicted furnace exit gas temperature was 18°F (10°C) lower than the predicted current baseline as found operation. Also the furnace waterwall heat absorption was essentially equal at 625 x 10^6 Btu/hr (157 x 10^6 Kcal/hr). And finally, the fly ash carbon content was predicted to remain at a very low level.

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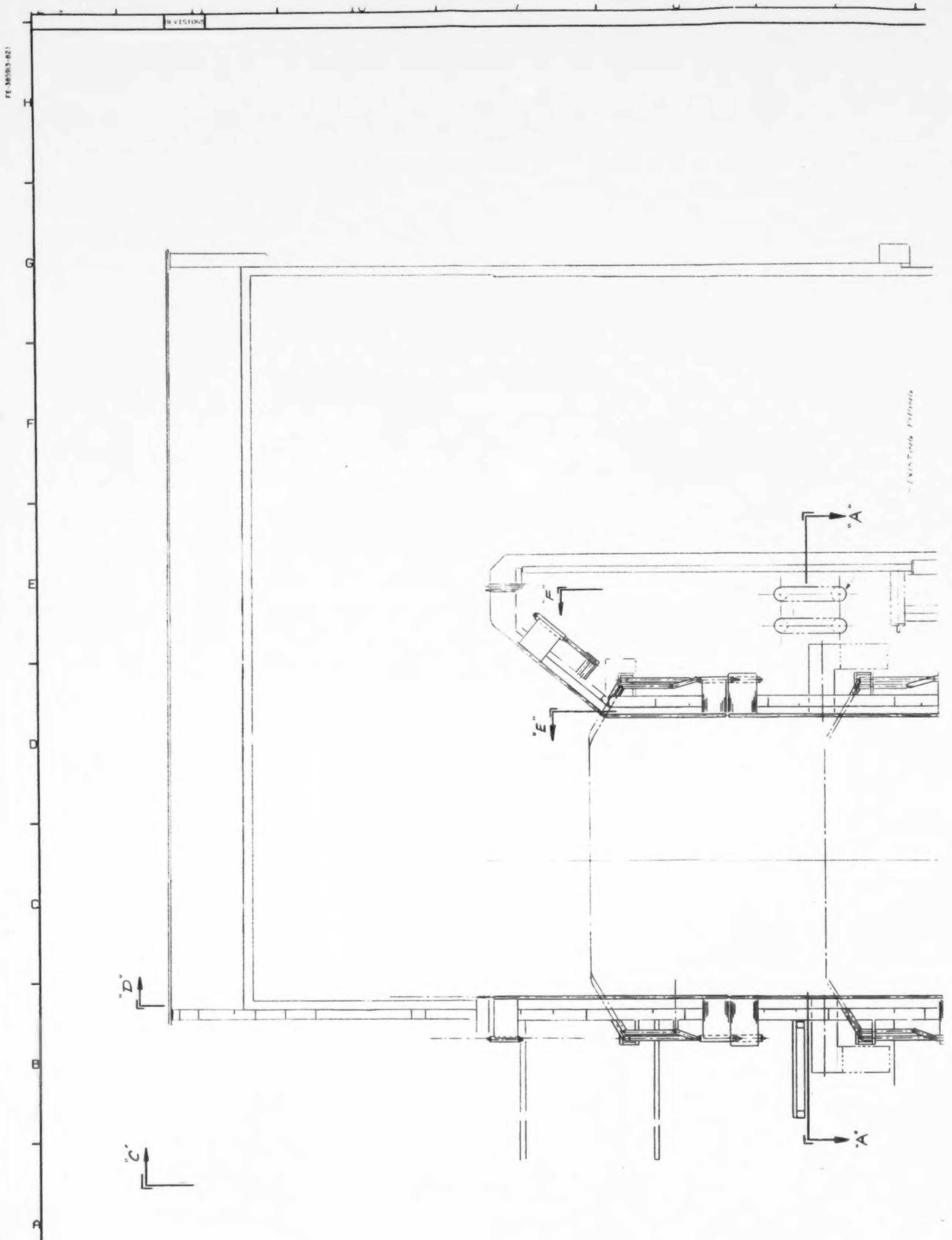
APPENDIX A

REBURN SYSTEM GENERAL ARRANGEMENT DRAWINGS

Dwg No.	Page No.
SK901078-1	A-2/3
SK901078-2	A-4/5
SK901078-3	A-6/7
SK901078-4	A-8/9
SK901078-5	A-10/11
SK901078-6	A-12/13


REVISIONS
FE-30593-821
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EXISTING PIPING
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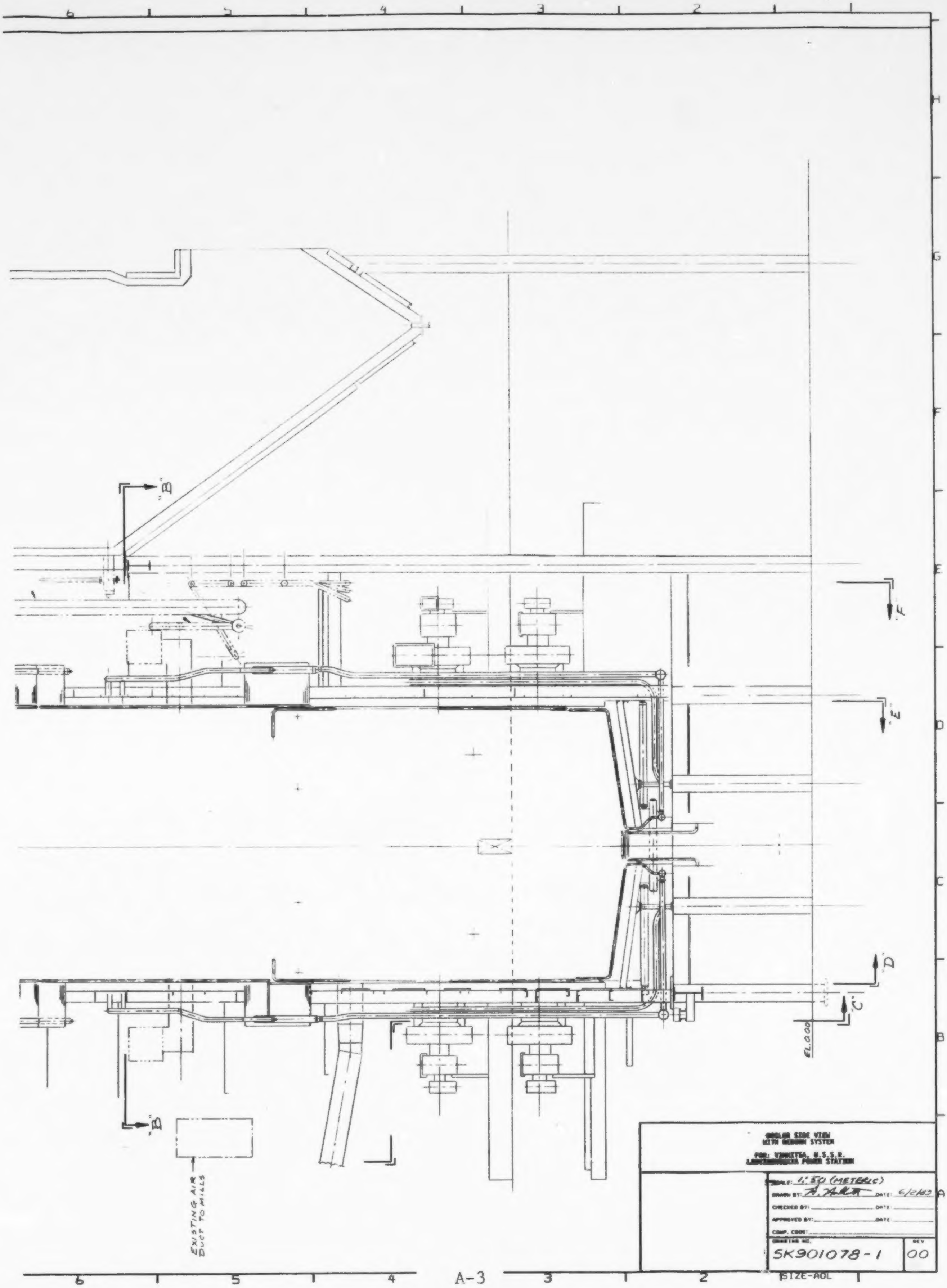
"F"
"E"
"D"
"A"
"C"



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"F"
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EL 0.000
"B"
EXISTING AIR DUCT TO MILLS
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BOILER SIDE VIEW
WITH REBURN SYSTEM

FOR: VINNITSA, U.S.S.R.
LADYZHINSKAYA POWER STATION

SCALE: 1:50 (METERIC)
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APPROVED BY: ______ DATE: ______
COMP. CODE: ______

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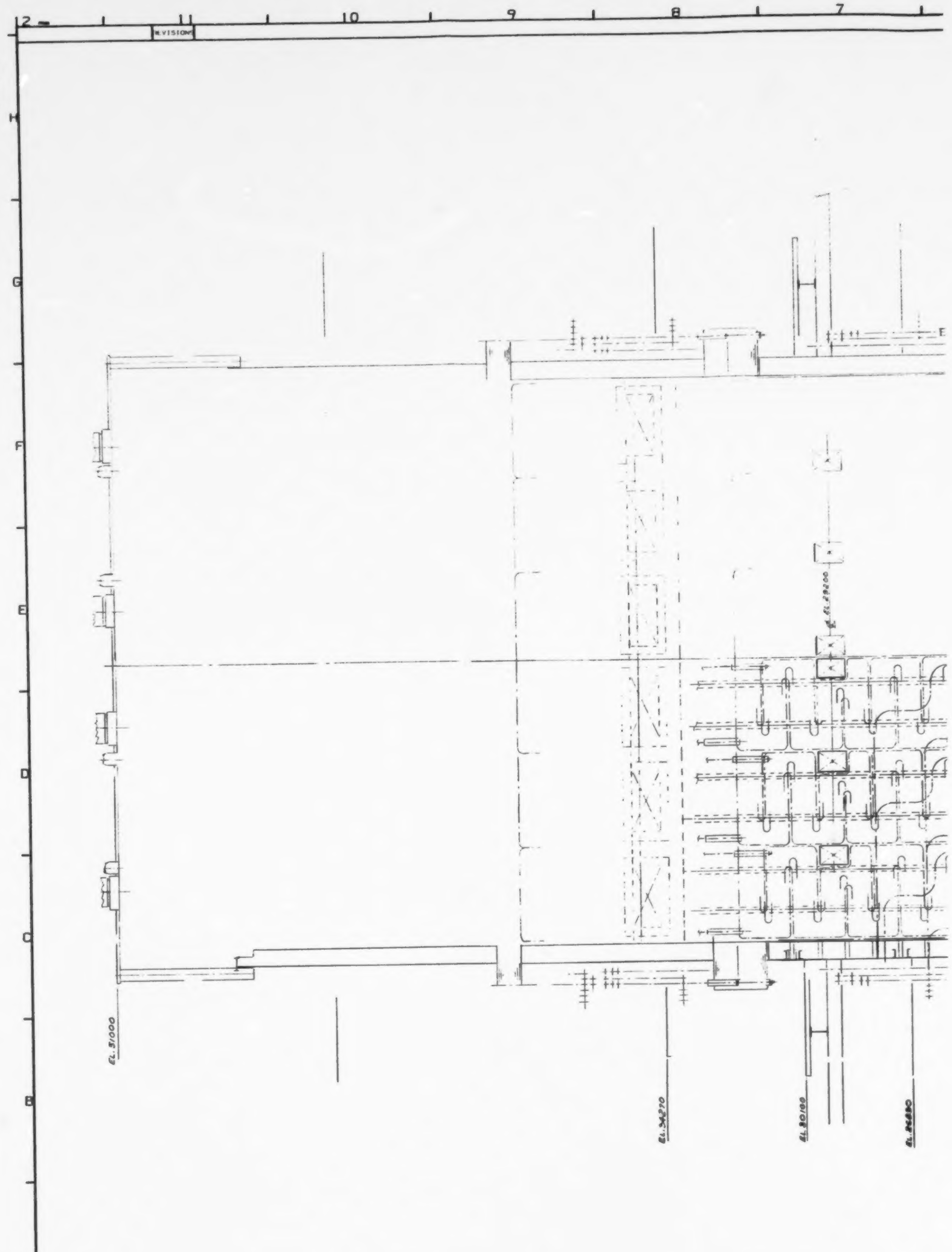
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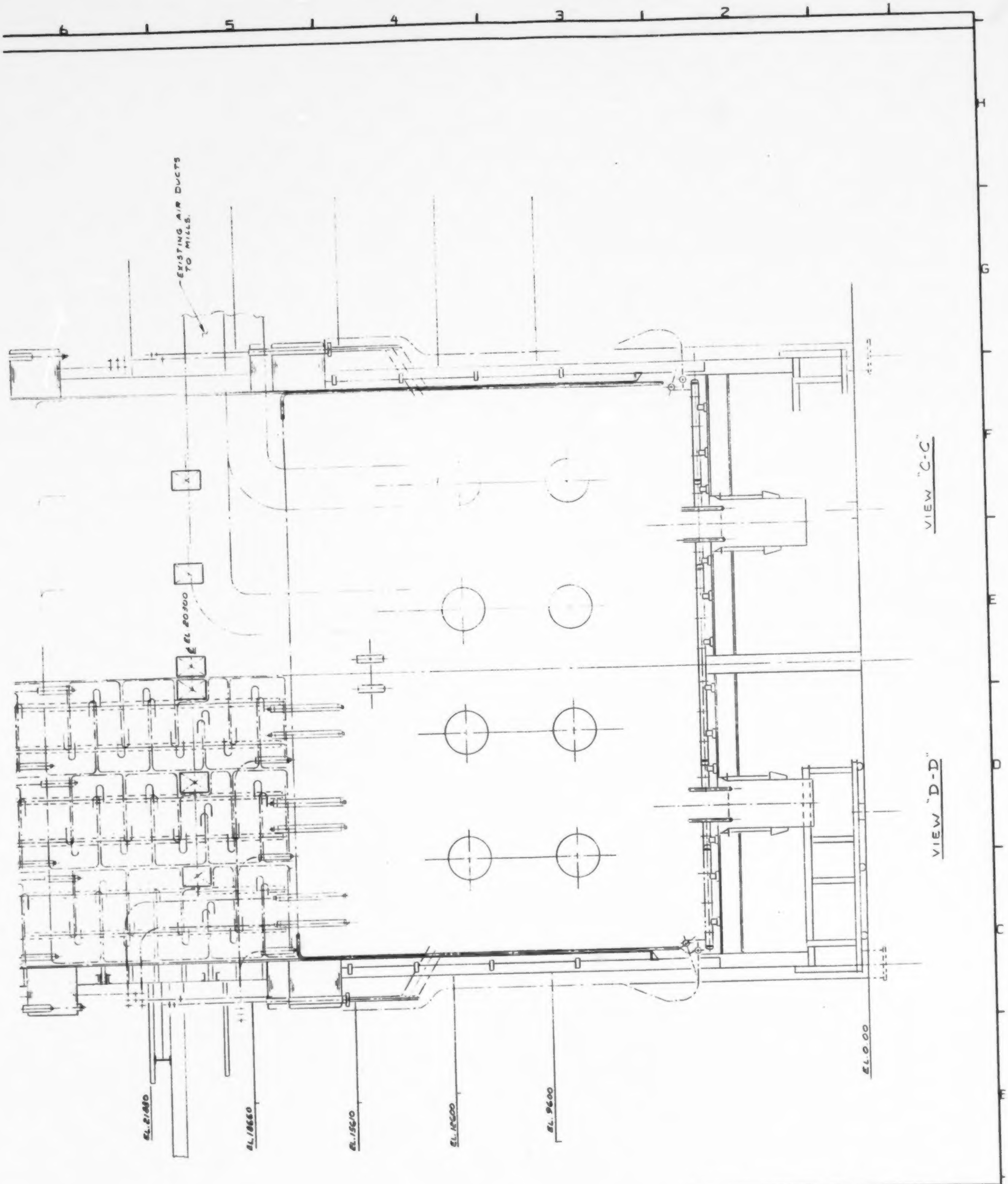
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EL 20300
VIEW "C-C"
VIEW "D-D"
EL.21880
EL.18660
EL.15610
EL.12600
EL. 9600
EL.0.00
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BOILER FRONT VIEW
GETR REBURN SYSTEM

FOR: VINNITSA, U.S.S.R.
LADYZHINSKAYA POWER STATION

SCALE: 1:50 (METERIC)
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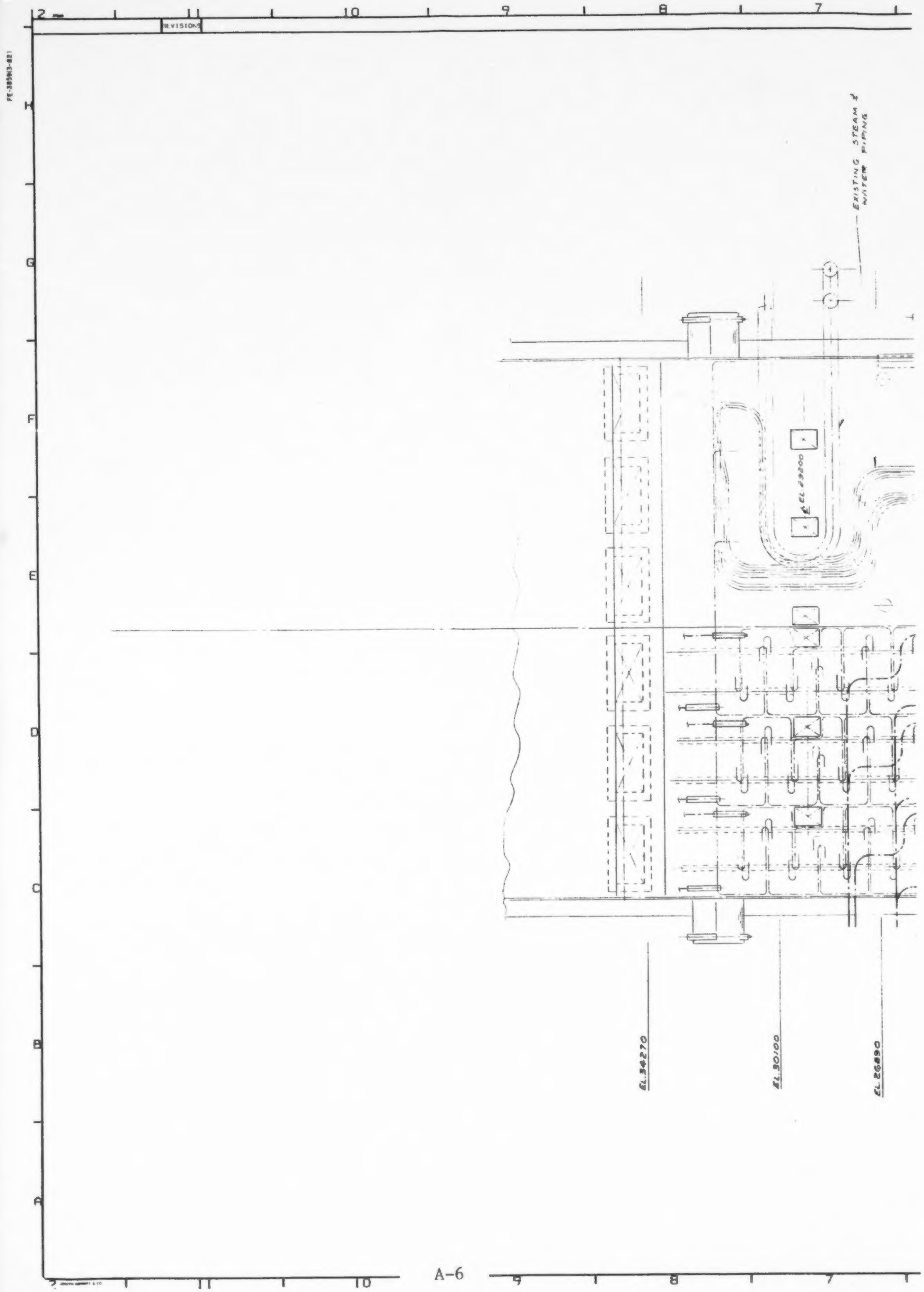
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REVISIONS
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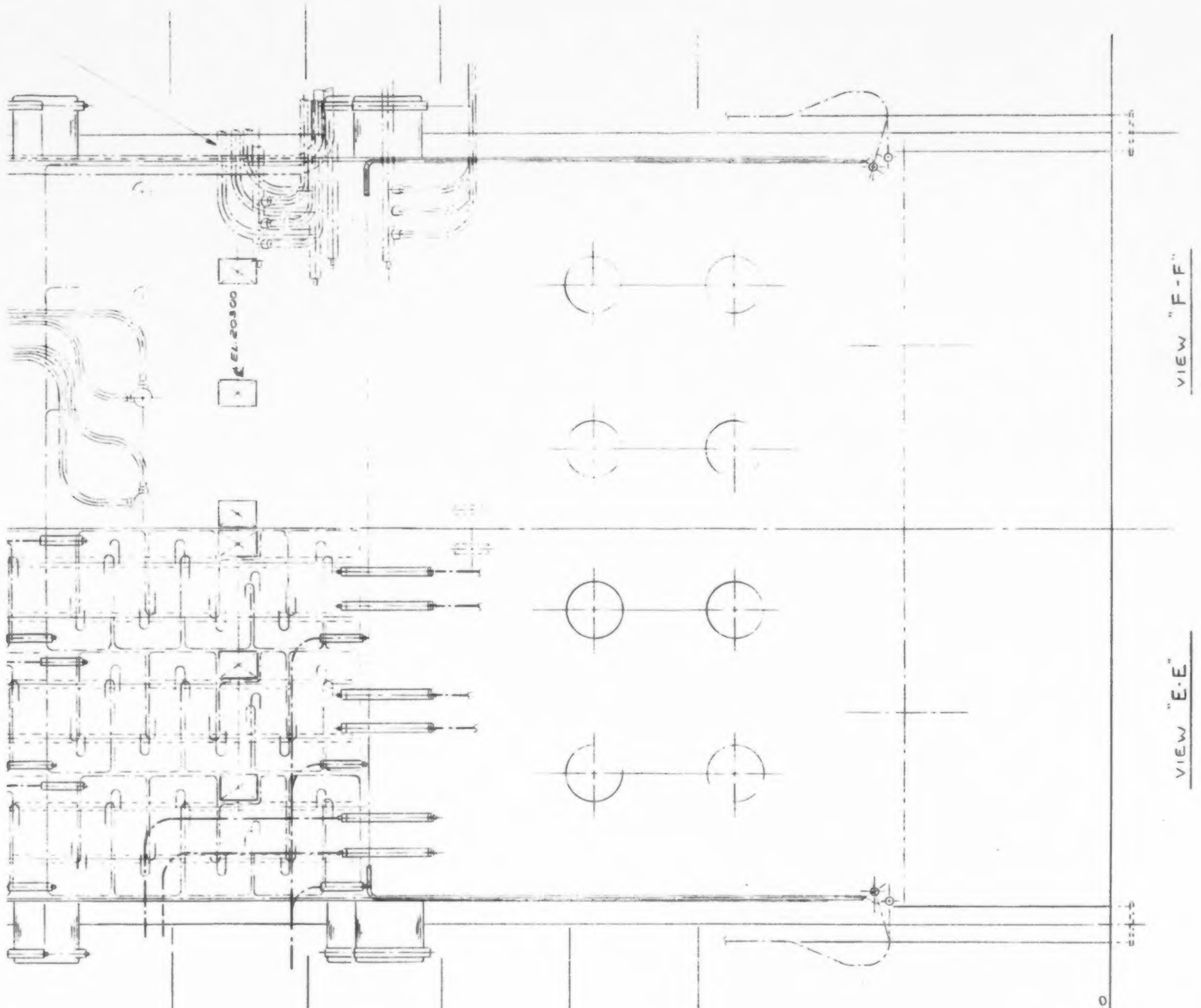

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EL.20300
VIEW "F-F"
VIEW "E-E"
EL.21880
EL.18660
EL.15610
EL.12600
EL.9600
EL.0.00

BOILER REAR VIEW
WITH REBURN SYSTEM

FOR: VINNITSA, U.S.S.R.
LADYZHINSKAYA POWER STATION

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APPROVED BY: DATE:
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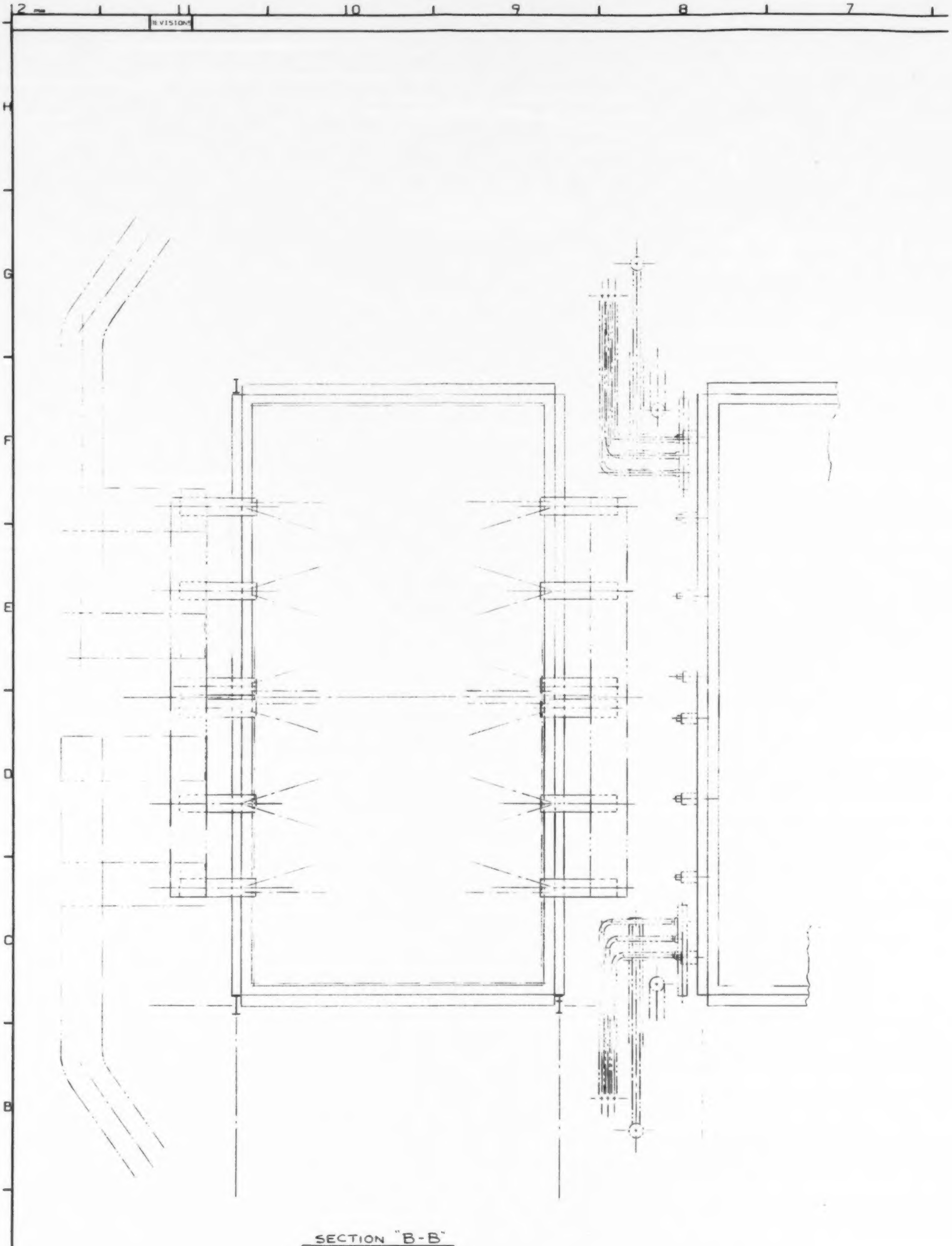
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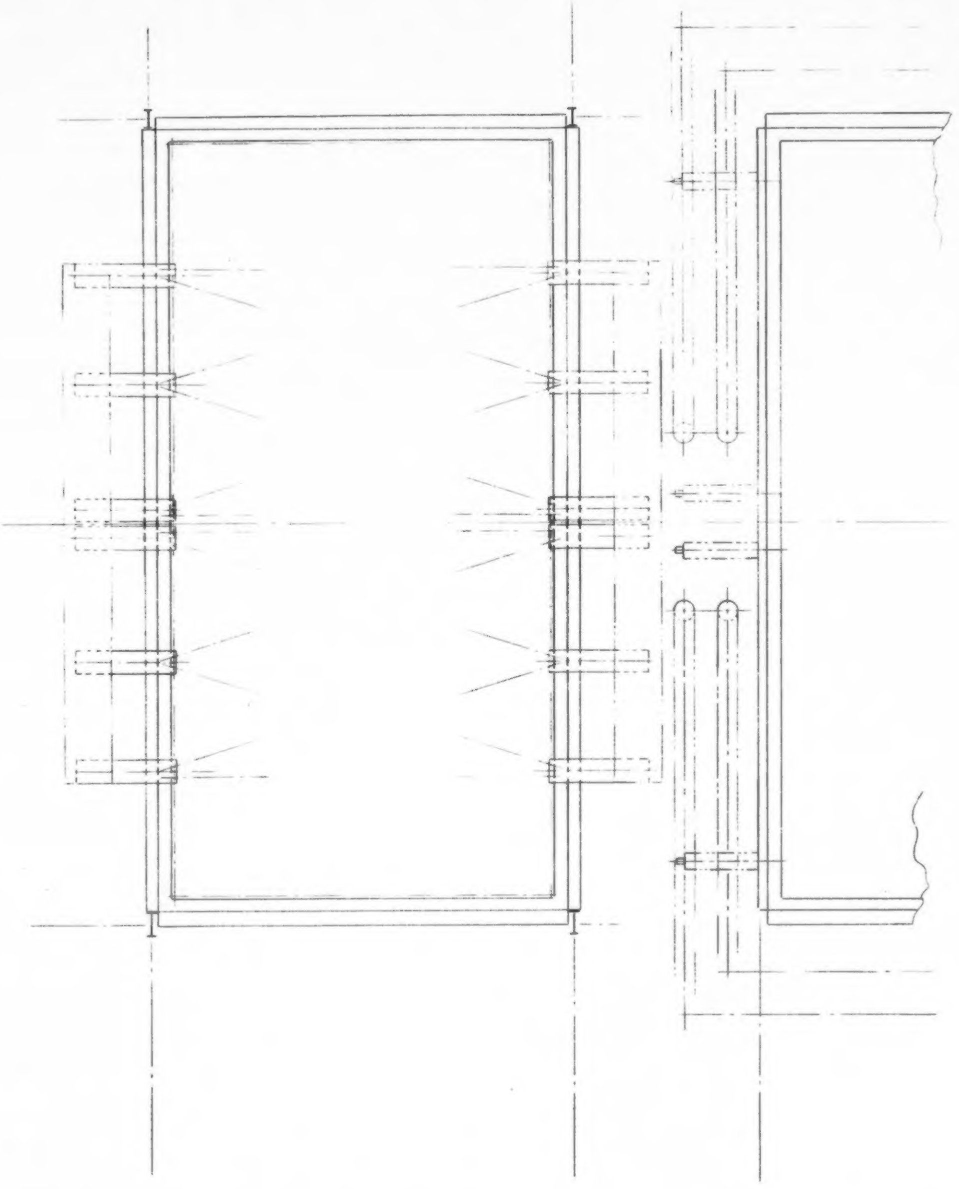
SECTION "B-B"



SECTION "A-A"

BOILER PLAN VIEWS "A-A" & "B-B"
WITH REBURN SYSTEM

FOR: VINNITSA, U.S.S.R.
LADYZHINSKAYA POWER STATION

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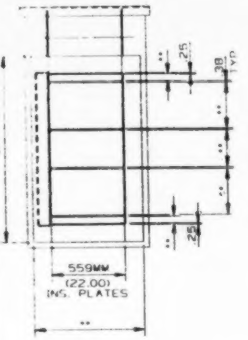
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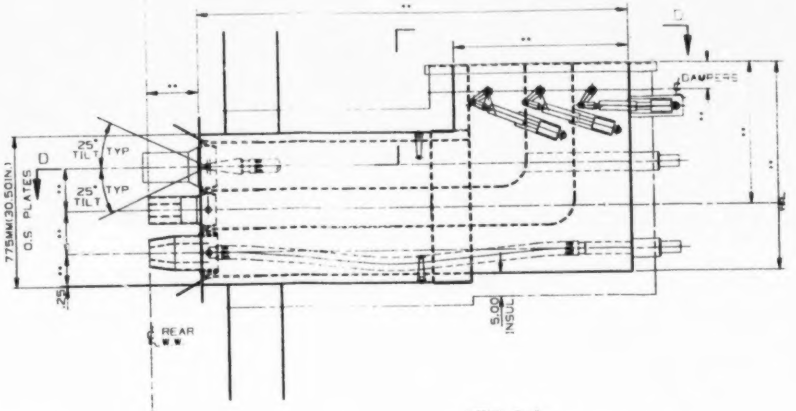
559MM
(22.00)
INS. PLATES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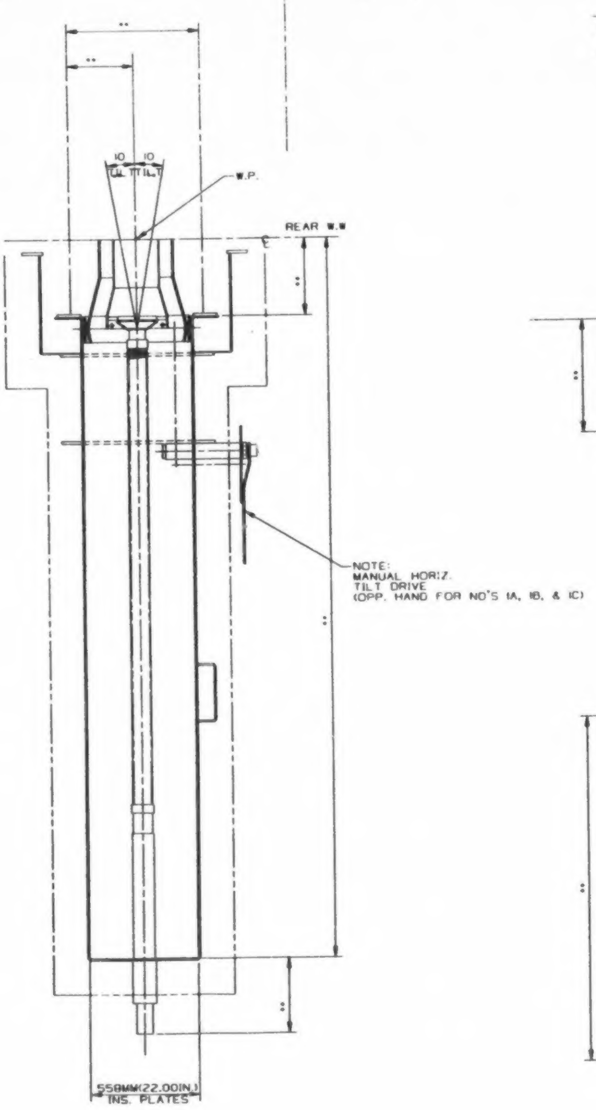
DAMPERS
25° TILT TYP
25° TILT TYP
D
775MM(30.50IN.)
O.S PLATES
.25
℄ REAR W.W.
5.00 INSUL

VIEW A-A
SIDE ELEV.
FUEL INJECTOR NO'S 1B & 1E
SCALE:1.00=12.00


10 TILT
10 TILT
W.P.
REAR W.W
NOTE:
MANUAL HORIZ.
TILT DRIVE
(OPP. HAND FOR NO'S 1A, 1B, & 1C)
558MM(22.00IN.)
INS. PLATES

SECTION C-C
FUEL INJECTOR NO'S 1A, 1B, 1C, 1D, 1E, & 1F
SEE SECT. E-E FOR
DIM'S. NOT SHOWN
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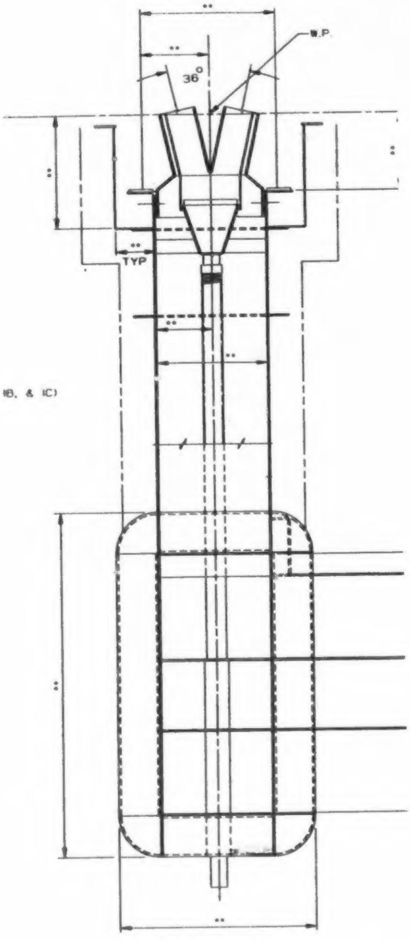

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TYP FOR FUEL INJECTOR
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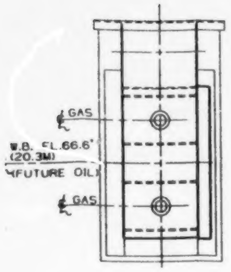
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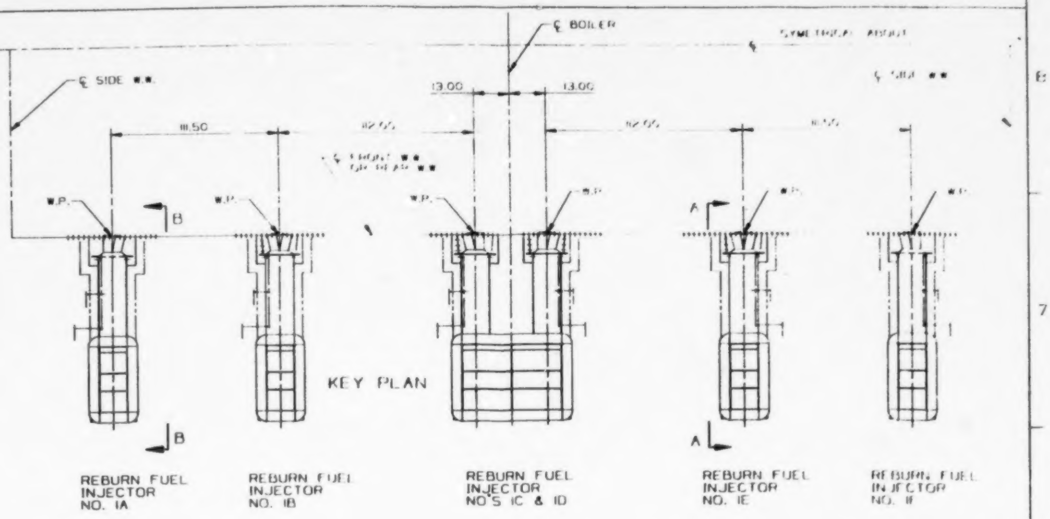
(20.3M)
℄FUTURE OIL
℄ GAS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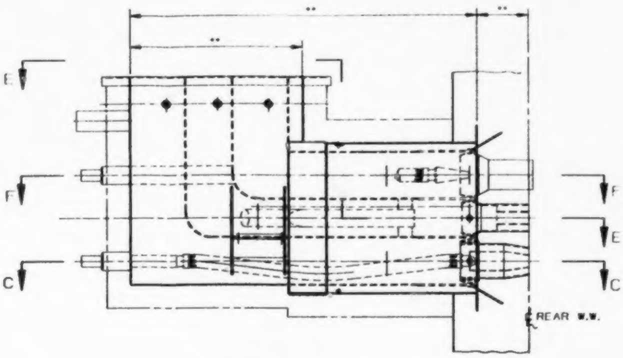
KEY PLAN
REBURN FUEL INJECTOR NO. 1A
REBURN FUEL INJECTOR NO. 1B
REBURN FUEL INJECTOR NO'S 1C & 1D
REBURN FUEL INJECTOR NO. 1E
REBURN FUEL INJECTOR NO. 1F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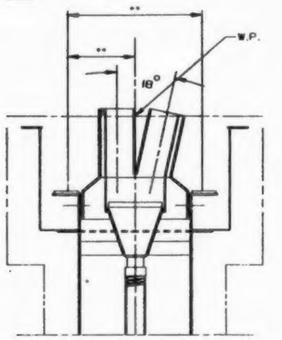
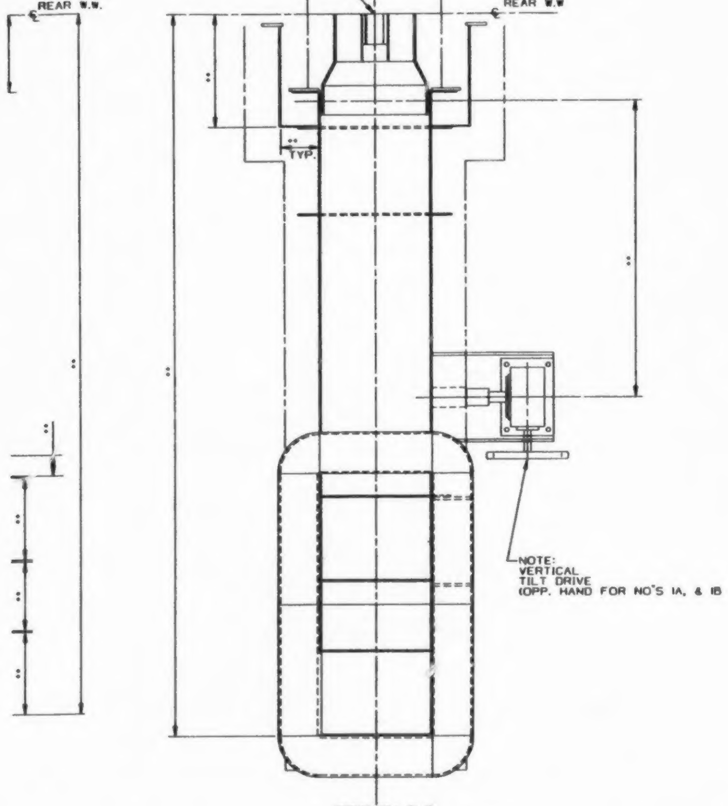
℄ REAR W.W.

VIEW B-B

SIDE ELEV.
FUEL INJECTOR NO'S 1A, 1C, 1D, & 1F
FOR DIM'S NOT SHOWN
SEE VIEW A-A
SCALE:1.00=12.00



SECTION F-F
FUEL INJECTOR NO'S 1A, & 1D AS SHOW
FUEL INJECTOR NO'S 1C, & 1F OPP.HANI


W.P.
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VERTICAL
TILT DRIVE
(OPP. HAND FOR NO'S 1A, & 1B

SECTION E-E
FUEL INJECTOR NO'S 1A, 1B, 1E & 1F
FOR DIM'S NOT SHOWN
SEE SECT. C-C
SCALE:1.50=12.00

CONTRACT NO.	UNIT NO.
WINDBOX ARRANGEMENT-REBURN FUEL INJECTORS FOR:VINNITSA,USSR LADYZHINSKAIA POWER STATION	
SCALE: ••	
DRAWN BY: JRL	DATE 6/20/89
CHECKED BY: MJ (PREL.)	DATE:
APPROVED BY:	DATE
COMP. CODE: 11-48-31-0000-00	
DRAWING NO. SK901078-5	REV. 00

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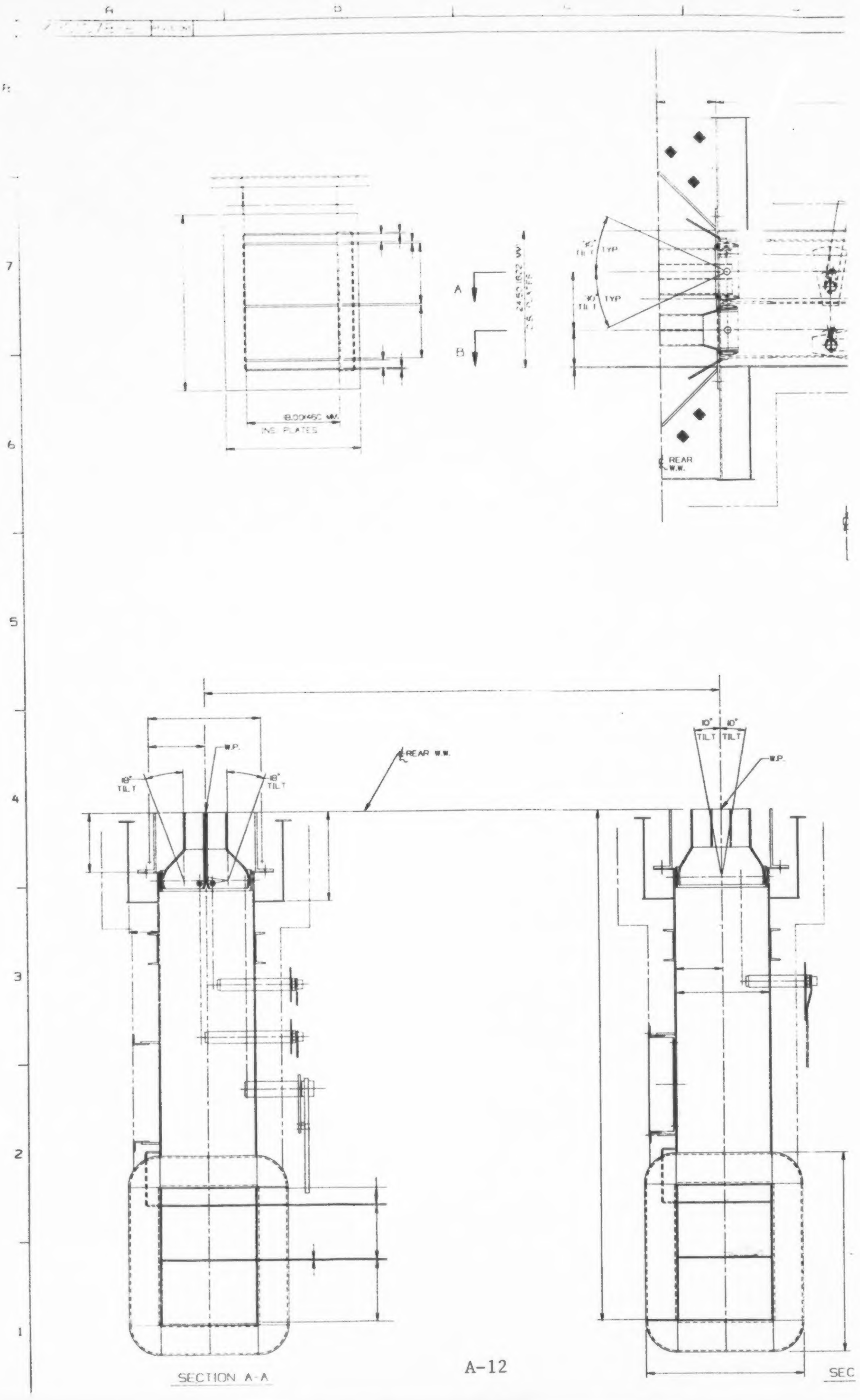
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B
18.00(450 MM)
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10° TILT TYP
℄ REAR W.W.
W.P.
18° TILT
18° TILT
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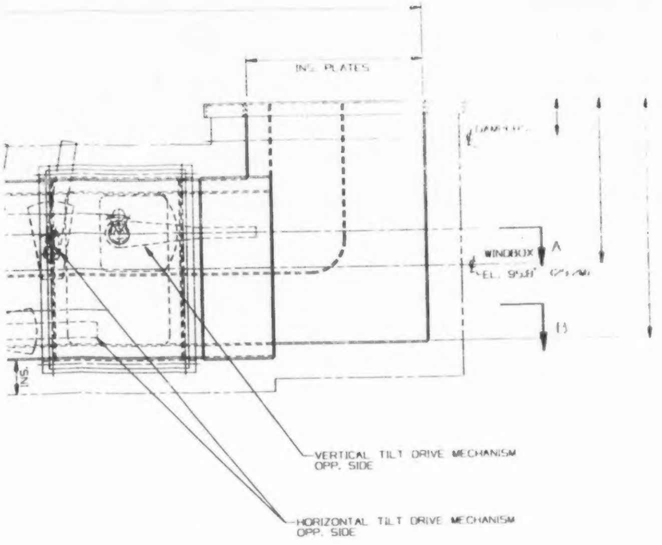
10° TILT
10° TILT
W.P.
SECTION A-A
SEC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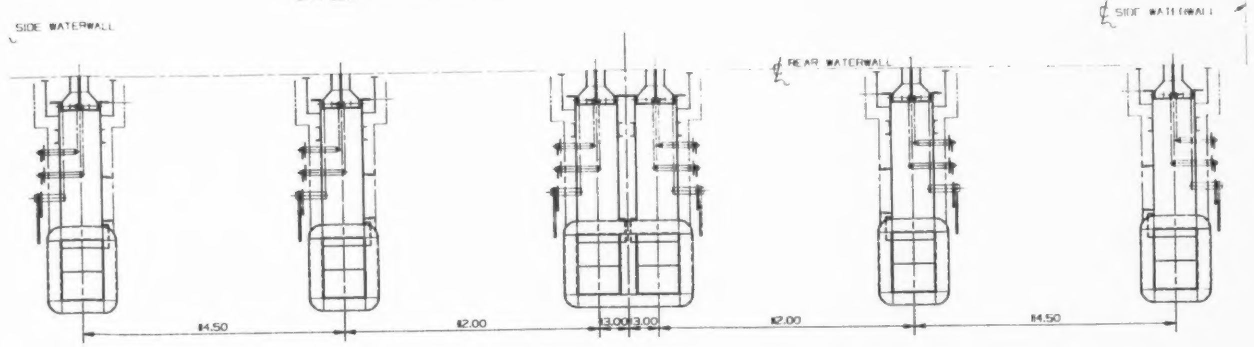
VERTICAL TILT DRIVE MECHANISM OPP. SIDE
HORIZONTAL TILT DRIVE MECHANISM OPP. SIDE

TION B-B


SIDE WATERWALL
REAR WATERWALL
SIDE WATERWALL
14.50
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12.00
14.50

KEY PLAN @
REAR WATERWALL

TYPICAL @ FRONT & REAR
WATERWALLS OF BOILER

CONTRACT NO.
UNIT NO.

WINDBOX ARRANGEMENT-BURNOUT AIR
FOR:VINNITSA,USSR LADYZHINSKAVA POWER STATION

SCALE: NONE
DRAWN BY: M.JOREY DATE: 6-20-89
CHECKED BY: JRL (PRELIM.) DATE: 6/21/89
APPROVED BY: DATE
COMP. CODE 11-48-31-0000-01
DRAWING NO. SK901078-6
REV 00